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[*Continued on page* (*III*) *of Cover.*

ELECTRIFICATION OF THE PARIS-ORLÉANS AND MIDI RAILWAYS

By A. BACHELLERY.

[*Paper first received* 6*th May, and in final form* 22*nd July*, 1937; *read at a Joint Meeting of* THE INSTITUTION *and the* BRITISH SECTION OF THE SOCIÉTÉ DES INGÉNIEURS CIVILS DE FRANCE 18*th November, and before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 15*th November*, 1937.]

SUMMARY

The author describes the work done since 1923 on the Midi and Paris–Orléans Railways, which were amalgamated a few years ago. The paper concludes with an account of the results obtained from electric traction.

INTRODUCTION

Since 1923, when I read before The Institution a paper on the Midi Railway,* there have been many changes in France in connection with electric traction. Since 1934 the Midi and Paris–Orléans Railways have formed a single system and the electrification work of the two railways has been placed under common direction.

In 1923, electrification of the French railways had only just passed the experimental stage. The general principles to be adopted in the electrification of all the railways on a standard basis had been decided, plans had been drawn up, and equipment was being actively put in hand. But electric traction was only in operation on the suburban section of the Paris–Orléans Railway (26 km., 600-volt direct-current third-rail system) and on 280 km. of the Midi Railway (55 km., 850-volt direct-current third-rail; 46 km., 12 000-volt single-phase; and 179 km., standard 1 500-volt direct current). In the intervening period new developments have rapidly taken place, and at present there are 2 518 km. of electrified lines on the Paris–Orléans and Midi Railways, comprising 5 524 km. of track. The new permanent-way equipments are of the overhead 1 500-volt direct-current type. The suburban section of the Paris–Orléans Railway has been re-equipped on the standard system. Electrification has thus been carried out on a great number of routes presenting very diverse features. It covers nearly the whole of the mountain lines in the Pyrenees, including the two Transpyrenean routes where there are gradients of over 1 in 25. But in recent years it has been mainly adopted on heavy-traffic lines where a high consumption of coal per kilometre of route allows sufficient economy to make electrification a paying proposition.

It was on this account that the Paris–Orléans company electrified their lines from Paris to Vierzon in 1926, and from Orléans to Tours in 1933; and it was for the same reason the Midi company, after completing their Toulouse–Dax line, started electric traction in 1927 between Bordeaux, Biarritz, and Hendaye. Since the amalgamation of the two companies electrification has been pushed on from Vierzon to Brive, and between Montauban and Sète. In addition, construction has been begun between Tours and Bordeaux, and next year (1938), when this has been completed, electric locomotives will be able to run without interruption from Paris to Irun, on the Spanish frontier, a distance of 820 km.

Electrification at present covers 22 per cent of the length of the whole system, and handles 50 per cent of the traffic. In a few years' time, when some new developments under consideration have been carried out, these figures will be respectively 30 and 70 per cent.

ENERGY PRODUCTION AND TRANSMISSION

Consumption of electrical energy for the railways amounted in 1936 to 470 million kilowatt-hours, corresponding to an economy of coal on the locomotives of more than 1 million tons. This energy is mainly produced in hydro-electric plants belonging to the railways or to allied firms. A part, however, is drawn from steam plants connected to the railways' high-voltage lines, as will be explained later in this paper. The Orléans company are the owners in Central France of two water-power plants with an output of 152 000 kW. The Midi company own seven water-power plants in the Pyrenees, with a total installed capacity of 135 000 kW. Their average annual production is over 900 million kilowatt-hours, and the surplus energy is sold for use in industry or for public distribution.

The Paris–Orléans and Midi Railways' policy regarding electricity generation fits in with the general electrification practice of the country. Standard 3-phase 50-cycle current is generated, allowing interconnection with the public distribution systems; and the railways' high-voltage lines permit of the transmission of not only their own energy but also that generated by other undertakings. The Orléans high-voltage system, comprising 90-kV and 220-kV lines, runs north to Paris, and is connected to various water-power plants and to the large steam plants that furnish Paris with light and power. The Midi system comprises 60-kV and 150-kV lines: 36 generating plants, either water-power or steam, are connected to it and run in parallel. With an annual output of 2 000 million kilowatt-hours, these plants provide practically all the electric production in the south-west of France. To ensure correct management of these two complicated systems of generating plants and transmission lines, central dispatching is provided on both of them. The next step will be to connect the two systems, which up to now have been left independent. Each system is composed of two kinds of lines—first, very high-voltage lines (150 kV or 220 kV) used for long-distance transmission; and secondly, a network of lower-voltage lines (60 kV or 90 kV) running along the railway and used to distribute power to the substations. There are 422 km. of 220-kV lines, 805 km. of 150-kV, 1 220 km. of 90-kV, and 1 614 km. of 60-kV, making a total of over

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* *Journal I.E.E.*, 1924, vol. 62, p. 213.

4 000 km. These figures will increase with the completion of the new electrifications now in hand.

All the recently-constructed high-voltage lines employ steel-reinforced aluminium cable carried by suspension insulators. Interconnection between lines carrying different voltages is provided in large transformer stations, of which there are 10 in service, with a total rating of 720 000 kVA. Most of them are provided with synchronous condensers for voltage regulation. The total reactive kVA of these machines is 267 000. One of them, installed in 1933 at Portet St. Simon on the Midi Railway, is of the outdoor hydrogen-ventilated type and is rated at 30 000 kVAr. It is, the author believes, the only machine of its type in Europe, and it gives entire satisfaction.

SUBSTATIONS

Substations, where 3-phase high-voltage power is transformed into 1 500-volt direct current, are built along the track at distances varying generally from 20 to 25 km., with a maximum of 30 km. on some secondary lines and a minimum of 10 to 15 km. on suburban or mountain lines where multiple-unit or double traction is used. There are at present 111 of these substations, with an installed capacity of 357 000 kW. They generally consist of an outdoor transformer station and a closed building, inside which are the convertor groups, switchboard, and control apparatus. The convertors used are of different kinds: two of the Midi substations, where it is necessary to regulate the voltage on the high-voltage side, are provided with synchronous motor-generator sets, but in general either rotary convertors or mercury rectifiers are used.

The rotary convertors are, for the most part, groups of two 750-volt units connected in series. They have a compound characteristic and their standard rating is 2 000 kW.

On the Midi Railway are to be found a large number of 1 500-volt rotary convertors in single units; but in consequence of their limited power (1 000 kW hourly rating as a maximum) such machines have not been employed in the latest electrifications.

The mercury rectifier for heavy traction was first introduced on the Midi Railway in 1923, and the five substations in which this type of machine was then installed are still running in a very satisfactory way.

Since then a great number of new substations have also been equipped with rectifiers, including 23 on the Midi Railway and 4 (projected) on the Tours–Bordeaux section of the Paris–Orléans Railway. Some new features have been introduced in the construction of the rectifiers. Instead of 12-phase double-unit groups, 6-phase single units are now used. The hourly rating of these units is 2 000 kW. Induction on telephone lines through the slight ripple of the current is prevented by appropriate filters. Polarized anode grids have been inserted for protection against arcing. Excited grids for regulation of d.c. voltage in the rectifiers are being experimented with in a few substations, in order to obtain a compound characteristic. These experiments have not yet yielded definite results, however, and the rectifier substations have up to now been run practically with a shunt characteristic, which proves sufficient. Each convertor unit is generally protected against short-circuit on the direct-current side by a quick-acting circuit-breaker. In many cases this does not cut out the line altogether, but only inserts a resistance, the final interruption being effected by a second breaker. Protection against voltage surges is provided on the high-voltage as well as on the low-voltage side through various types of lightning arresters, inductive coils, or shunted condensers.

Automatic control of the substations has been extensively applied by both the Midi and the Paris–Orléans companies: 60 substations are at present equipped in this way. Automatic control is, however, only applied to the convertors and d.c. feeders. The connections between substations and high-voltage lines are always made manually; this introduces no difficulty, one man being, as a rule, placed in charge of each substation. Either one substation in each group of four, or one convertor unit in each substation, is left running continuously, according to the schedule; starting and stopping are often automatically controlled by clockwork. Extra units are automatically set to work or stopped by voltage or current variations on the line. An automatic stopping-device is also provided for emergencies, such as a hot bearing.

These automatic substations have been found quite successful and very economical, cutting down energy consumption and allowing a considerable reduction of operating staff.

LINE EQUIPMENT

The overhead-line equipment is of the compound catenary type, but there is some difference between the arrangements employed on the Midi and on the Paris–Orléans lines. The Midi catenary is made up of a steel messenger cable, an auxiliary messenger, and a contact wire, the two last-mentioned being made of grooved copper of 0·155 sq. in. cross-section. In the latest applications, however, the copper-wire section has been increased to 0·24 sq. in., and no special difficulty has been experienced as a result. On curves, the line has no pull-offs and follows the same curvature as the track, the hangers taking an inclined position. On straight sections, pull-offs consisting of helical springs fixed to the auxiliary messenger are used to maintain the catenary in its proper place. On the Paris–Orléans lines the messenger cable is of bronze, of 0·18 sq. in. cross-section. It supports an auxiliary messenger made of 0·16 sq. in. copper, from which two copper contact wires of similar gauge are alternately suspended by loose hangers, so as to suppress " hard points." This last construction necessitates the use of pull-offs on curves as well as on straight sections, the catenary being in both cases kept rigidly in a vertical plane. Line conductivity is so arranged as to limit voltage-drop to a maximum of 20 % under the worst circumstances. When necessary, copper or aluminium feeders are added for this purpose.

After trying a great number of different types of supports for the catenary, both companies have now fixed their choice on steel lattice poles with brackets. For double-track lines the Paris–Orléans latest type has separate supports for each track, so limiting the consequences of a breakdown, whereas the Midi company have adopted a double-track bracket on account of the difficulty of shifting the telegraph lines.

Suspension insulators are now used for the catenary as well as for the high-voltage lines. Experience has fixed the maximum length of the catenary spans at about 60 metres on straight sections, and less on curves. Track rails are connected at the joints with copper cable bonds welded to the rails or to cores forced into holes in the web of the rails.

Air-gap sectionalizing of the contact line is provided at intervals of about 4 km. On the Paris–Orléans line this is completed by sectionalizing stations, which are placed half-way between consecutive substations and which contain quick-acting circuit-breakers connected by a pilot wire to the similar apparatus in the substations, so as to ensure the section being made dead in case of trouble.

On main lines, energy for light and power in the stations, including lighting of the signals, is distributed along the track at 5–15 kV by a 3-wire line mounted either on the same supports as the catenary or on special supports.

LOCOMOTIVES AND MOTOR-COACHES

The Paris–Orléans and Midi system possesses 638 electric locomotives and 152 motor-coaches. The locomotives belong to three main types: high-speed passenger locomotives, locomotives for ordinary passenger and freight trains, and shunting locomotives.

The high-speed passenger locomotives, 102 in number, have mostly a 2-D_0-2 design, i.e. 4 independent driving axles mounted in the main frame, with a guiding bogie at each end. The total weight is 125–140 metric tons, and the adhesive weight about 80 tons. The motors are entirely spring-borne. These locomotives have been tested up to 150 km. per hour, but the permitted speed does not at present exceed 130 km. per hour.

The 2-C_0-2 locomotives built about 1925 by the Midi company are still running. But this type, with vertical twin motors and bevel-gear transmission, has not been reproduced on account of clearance conditions forbidding an increase in the motor rating, and also because the maintenance expenses proved to be relatively high.

The motors on the 2-D_0-2 locomotives are horizontal and mostly of the twin-armature type, the two armatures being permanently coupled in series. One experimental locomotive has 3 armatures per motor; this arrangement allows a specially convenient system of motor couplings. The hourly rating of these locomotives is 3 900–4 800 h.p. Transmission between the motors and the axles is obtained through plain gears, according to either the Buchli or a quill-drive design. The motor control is electro-pneumatically operated. Some of these locomotives, designed to take express trains down long 1 % grades, are arranged for regenerative braking, which has proved quite successful at speeds varying from 25 to 140 km. per hour. When regenerating, the motors are separately excited with current supplied at variable voltage by a special motor-generator set.

The majority of the electric locomotives on the Paris–Orléans–Midi system are of the $B_0 - B_0$ type (two 4-wheel driving bogies). There are 521 such locomotives; their hourly rating varies from 1 400 to 1 800 h.p., and their weight from 72 to 80 tons. They all have nose-suspended geared motors, wound for the full 1 500 volts. According to the gear ratio, the maximum speed varies from 60 to 105 km. per hour. The majority have a maximum speed of 90 km. per hour, and are so arranged that three different methods of connecting the motors are possible, thus enabling them to draw either passenger or freight trains. At speeds over 80 km. per hour this type of locomotive requires special devices to prevent "nosing." On the Midi locomotives this trouble is prevented by coupling the bogies together with a drawbar and buffers, and on some of the Paris–Orléans locomotives which have independent bogies a flexible coupling device has been added between these.

The Midi locomotives of this type are largely in service on grades steeper than 1 in 50, and are therefore fitted with an electric brake which is normally used for checking the train on the descent. This brake is of either the rheostatic or the regenerative type. The rheostatic brake was formerly considered the safer and was exclusively used on freight trains, which were not fitted with air brakes. Freight trains are now equipped with continuous braking, and regeneration is adopted on all kinds of trains on the steep down grades, the only condition being that the convertors in the substations must be capable of returning energy to the line on the high-voltage side. (This condition is not satisfied where mercury rectifiers are used.) In addition to the above, all the Paris–Orléans and Midi electric locomotives have an automatic air brake and a direct, adjustable air brake.

The shunting locomotives, 15 in number, are mostly old 2-bogie locomotives built for suburban service on 600-volt direct current. The original motors have been kept, but the control apparatus has been replaced by a convertor group operating on the Metadyne system, which transforms the 1 500-volt line current into variable-voltage current for the motors and thus provides for speed regulation. These locomotives have proved very efficient and economical. Another type, still under test, is a C-C machine for heavy yard service. It is mounted on two 6-wheel bogies, with four nose-suspended motors and connecting rods.

The motor-coaches are mainly used for suburban service in the Paris district. They are 2-bogie cars with four nose-suspended geared motors coupled two in series. The hourly rating varies from 700 to 1 000 h.p., the weight from 56 to 74 tons, and the maximum speed from 90 to 100 km. per hour. Each motor-coach has 82 passenger seats. Trains are made up from two or three groups of one motor-coach and two trailers each, operated by multiple-unit control. On some branch lines in the Pyrenees motor-coaches are used weighing 57 tons, with 850 h.p. hourly rating, which can draw the passenger trains used on these lines.

The pantographs for current collection presented a difficult problem of standardization, as the two companies had each adopted a special type, corresponding to their particular catenary construction. When a high speed was attained the Paris–Orléans type of pantograph gave trouble on the Midi lines, and vice versa. After a good deal of research a standard pantograph was decided upon which would allow the locomotives to run equally well on either the Paris–Orléans or the Midi lines.

The passenger trains are heated electrically: 4 010 passenger coaches are already fitted with electric heating, which will also be applied to all new rolling-stock. The equipment consists of radiators installed under the seats and receiving the 1 500-volt line current from the locomotive. A special lock is provided in the electric couplers between the coaches to prevent uncoupling until the heating current has been cut off.

This system will probably be supplanted by another which is at present under test. It consists of a central air-heating device placed under each coach and receiving heat either from steam or from an electric current. The hot air emitted is sent by a fan through ducts to the various compartments, and automatic regulation of the temperature is obtained by thermostats operating the steam valve or the current-interruptor through an electric or a compressed-air control system.

FORTHCOMING DEVELOPMENTS

Since the amalgamation of the Paris–Orléans and Midi systems the new developments have been so directed as to establish connections between the electrified lines of the two companies. A first contact will shortly be made at Bordeaux, on the completion of the Tours–Bordeaux equipment. Another will be effected at Montauban when the 163-km. gap in the electrification between Brive and Montauban is filled up, as it is bound to be in a few years' time. This will establish a second end-to-end electrified line between Paris and the Pyrenees. These interconnections will result in a great improvement in the use of the electric locomotives, which will be run indiscriminately throughout the whole system.

Connections will be completed also between the two companies' electric transmission lines, so as to pool the energy resources of the generating plants of the two systems.

Lastly, an effort is being made to standardize the various types of equipment. As has been stated, this has already resulted in the adoption of a standard current-collecting apparatus for the locomotives: standardization of other parts of the locomotives and permanent-way equipment is also in preparation.

RESULTS ACHIEVED BY ELECTRIC TRACTION

Electrification has in some cases been adopted by the Paris–Orléans and Midi Railways as a technical necessity. On mountain routes, with declivities of over 3 in 100, steam traction often proved inadequate. The attainable speed and load of the trains were far too low, and the only way out of this difficulty was to divert a large part of the traffic towards indirect but easier routes. The electric locomotive has provided the means for regular operation of these lines. It has also allowed the construction of the Transpyrenean routes with gradients of over 1 in 25 and of the narrow-gauge Cerdagne Railway with its long grades of 6 in 100, which a steam engine could hardly climb by itself. Electric traction has proved to be no less a necessity on routes where there are long tunnels, both on mountain lines and on the underground terminus of the Paris–Orléans line in Paris, on account of the inconvenience arising from smoke. Moreover, the heavy traffic on the suburban lines near Paris could not be handled without the facilities afforded by electric multiple-unit reversible trains.

Even on ordinary main lines the technical advantages of electrification are most impressive. It is indeed a noteworthy fact that the Paris–Orléans company, who during the last few years have made very successful attempts to improve the power and fuel economy of their express steam locomotives, have, nevertheless, gone steadily on with their electrification work. The reason for this is easily found. The weight of fast passenger trains on the French railways is continually increasing on account of the trend towards metal construction of the coaches and a growing demand for comfort: such trains now often weigh 700 or even 800 tons. Their speed must also be raised in order to meet the severe competition with road transport, and this implies a large increase in tractive power. Whilst the continuous rating of the most modern passenger steam locomotives does not in practice exceed 2 500 h.p. on the drawbar, and it is only with great difficulty that the average fireman can stand the physical strain which this represents, the performance of the high-speed electric locomotive is easily 50 % higher, permitting great acceleration of heavy passenger trains. Between Orléans and Tours, for instance, several trains now maintain a schedule speed of 110 km. per hour. Similarly, on the 500 km. from Paris to Brive, where long grades of 1 in 100 are to be found, the express-train time has been cut down by more than an hour. Heavy goods trains have also been accelerated by the use of electric locomotives on such sections.

But for electric traction it would have been necessary to lay two extra tracks throughout the entire length of the 123-km. section between Paris and Orléans, through which the whole of the traffic of the Paris–Orléans and Midi system in and out of Paris has to pass. On account of the facilities afforded by electrification the 4-track construction has been limited to the 60-km. suburban section.

Apart from its technical advantages, electrification may be advantageous from an economic point of view. The Paris–Orléans and Midi companies have spent up to now on electrification work 3 730 million francs—595 million on generating plants, 2 060 million on transmission and distribution of electric power and on permanent-way equipment, and 1 075 million on locomotives and other rolling stock. This large financial outlay is offset by the economies obtained from electric traction. The reductions in operating costs (wages of crews, locomotive maintenance, cost of energy, etc.) consequent on electrification have often been demonstrated, and the experience of the Paris–Orléans and Midi Railways fully confirms such demonstrations. The average economy of coal on these companies' electrified lines is roughly 400 metric tons per kilometre of route, which is generally admitted to warrant the cost of electrically equipping the permanent way. In many cases the use of electric trains has made it possible to reduce train crews by one man. Further, the driver of an electric train can devote a larger proportion of his time to effective driving, and the higher speed of the train increases the distance he can cover each day. A typical instance of this is the 500-km. run from Paris to Brive, which is covered, on express trains, by a single driver in 5 hours 48 minutes. Moreover, electric locomotives being free from boilers, with their inherent drawbacks as regards loss of running time, can be used more continuously than steam locomotives, and consequently only about half as many are required for the same volume of traffic. The maintenance of electric locomotives is also much easier and cheaper: the distance they cover between overhauls is nearly double that for steam locomotives. To this advantage may be added the savings on water supply, ash-handling, cleaning of passenger trains, etc. The total reduction in operating expenses (including the cost of energy) for 1936 on the Paris–Orléans and Midi system due to electric traction is about 125 million francs, representing approximately 7 % of the capital invested in permanent-way electric equipment. As a consequence the ratio of expenses to receipts is lower on the Paris–Orléans and Midi system than on any other French railway.

Recent economic and social changes have tended to increase operating expenses, but this increase is far less in the case of electric traction than with steam traction. While the price of coal is steadily going up, that of energy generated in the companies' water-power plants is practically constant. Likewise the rise in price of such materials as steel, lubricating oil, etc., does not affect the cost of maintenance of electric locomotives as much as it does that of steam locomotives. Above all, the raising of wages and the shortening of working hours have less influence on electrified routes, owing to labour charges being a far smaller proportion of the total cost of transport. Indeed, the large amount of capital spent on electrification work by the Paris–Orléans and Midi companies, in carrying out a policy that has in the past been criticized for its audacity, has proved to be a profitable investment.

DISCUSSION AT THE JOINT MEETING OF THE INSTITUTION AND THE BRITISH SECTION OF THE SOCIÉTÉ DES INGÉNIEURS CIVILS DE FRANCE, 4TH NOVEMBER, 1937

Mr. Roger T. Smith: The paper describes a great engineering enterprise which has developed progressively for the past 15 years on non-constant standard lines.

In this country the question whether any particular electrification will be undertaken or is commercially sound is usually based on the trailing ton-miles per annum per single track of running rail—and this unit serves both for technical and for financial purposes. In France, where the electricity supply is derived mainly from hydro-electric stations, the favourite unit is the tons of coal saved by electrification per kilometre of route, and this number, of course, varies greatly with the conditions.

When I joined a railway at the beginning of this century the price of locomotive coal was still so low that the majority of the railways did not consider it to be worth while to undertake research on the locomotive considered as a heat engine, with the view of more economical design. The saving of coal, so important to the Continental railways, who had to import much or all of their fuel, was of little importance in England. All the available skill was devoted to making the steam locomotive as perfect a machine as it could be made, the chief idea being to reduce maintenance costs as far as possible; and the criticism was that the locomotives lived too long. Now that is all changed, and since the amalgamation of the railways the thermal efficiency of the British steam locomotive has been very greatly improved. At the present time the carriage of coal in this country by the railways still amounts to 36 % of the total freight traffic on the railways, and one-fifth of the total revenue of the railways comes from coal. The reduction of this traffic, if coal is burnt in power-station boilers instead of steam-locomotive boilers, has to be taken into account both from the point of view of loss of revenue and from that of interference with the business of the railway's best customer. This is one of the economic reasons why the case for electrification of main lines is very different here from what it is in France, Switzerland, or Italy. To those countries the saving of coal is all-important; while in England the economy arising from the saving of coal is slight, the cost of electric power being little different from the cost of coal power.

On the other hand, most of the suburban traffic in this country is above the economic limit of ton-mile density, and on many stretches of main line the ton-mile density is also above this limit. Electrification of certain sub-sections is being carefully considered by the railways, and these schemes are now beginning to be carried out.

Mr. C. E. Fairburn: When the French railways decided to tackle the problem of electrification in 1919–20, they sent a commission to inspect a good many of the electrifications of the world and to decide on which system they should standardize. The decision to employ one system only had a good deal to do with speeding up the electrification. The second important step taken by the French railways was to standardize the type of control to be employed for the locomotives.

There are three salient points that appeal to me in the paper: the first is the use of water power, the second the physical geography of the lines, and the third the system of accountancy.

With regard to the use of water power, it would be interesting to know what effect this has on the comparison of the price of coal on a steam-locomotive tender and the price of a unit of electricity. In the Weir Report on the electrification of all the railways of Great Britain the cost of electricity was given as slightly less than the cost of locomotive coal, the difference being 2 % of the total steam operating expenses. The cost of electricity on the London and North Eastern Railway scheme, however, was 12 % more than the price of coal on the locomotive tenders, and on the London, Midland and Scottish Railway scheme it was 9 % more. If the author could give corresponding figures for France it would be possible to compare the economies due to electrification in the two countries.

Turning to the question of the physical geography, the paper states that in France a great many gradients have been electrified, and we know that where there are heavy gradients the case for electrification is a good one. What percentage of the electrified track consists of gradients, and how have these gradients affected the average saving?

Finally, dealing with the system of accountancy, the author says on page 237: "The total reduction in operating expenses (including the cost of energy) for 1936 on the Paris–Orléans and Midi system due to electric traction is about 125 million francs, representing approximately 7 % of the capital invested in permanent-way electric equipment." Whatever the results may be when a line is completely electrified, I think it will be found that with partial electrification the cost of the electric locomotives is undoubtedly more than that of the steam locomotives. I should like to know, therefore, how the accountants dealt with this extra cost and on what grounds the locomotives are not taken account of in the capital charges.

Mr. F. Lydall: I agree with Mr. Fairburn that if more information could be given on some of the accountancy questions and upon how the calculations were made, such additional information would be welcome.

If one analyses the costs of operation of a comprehensive steam service one finds that the cost of coal and water used on the locomotives at present represents about 25 % of the total. Of the remainder, train wages, including wages of drivers, firemen, and guards, amount to about 40 %. If one regards electrification as a process whereby electric power is delivered to electric vehicles (locomotives or motor-coaches) in place of coal to steam locomotives, then the cost of electric power delivered is almost certain to be substantially higher than the cost of coal and water. Mr. Fairburn has referred to the Weir Report, and has said that in the case of one of the sections investigated the cost of electric power was higher than the cost of coal; but perhaps he has overlooked that the cost of power in this case includes the cost of transmission and conversion in substations; in fact, it is the cost of direct current delivered to the overhead lines. In these circumstances I think it is rather remarkable that the cost of power was no higher in relation to the cost of coal and fuel. My point, however, is that of the various items that have to be brought into the balance sheet when one is considering an electrification scheme, the biggest one is locomotive men's wages and guards' wages, and for a successful electrification scheme it is necessary to reduce substantially this and other items of expenditure.

I am rather surprised that some of the minor passenger trains in use on the Paris–Orléans and Midi Railways are not multiple-unit trains. It seems from the paper that multiple-unit trains are confined mainly to the suburban services round about Paris. Surely it would be desirable to employ those trains for considerable distances, and to take advantage of their elasticity and their suitability for single-man driving.

The paper states that in many cases the use of electric trains has made it possible to reduce train crews by one man, and a little later it states that the run from Paris to Brive is covered in 5 hours 48 minutes by a single driver. Does this mean one man in the locomotive, or a single locomotive crew?

So far as any arrangement of electrification can serve to enable the locomotive and train wages bill to be reduced, it is an important advantage. In one of the sections investigated for the Weir Report the reduction in the locomotive wages on goods working, due partly to the acceleration of services and partly to one-man operation, was found to be no less than 60 %; such a saving, of course, goes a long way towards justifying electrification.

Finally, I notice that there are only 15 shunting locomotives on the author's system; this seems to imply that the locomotive yards, sidings, etc., have not been equipped for electric working, which is a little surprising. Whatever may be said about the electrification of shunting yards, etc., as isolated installations, there can be no doubt that, as adjuncts to a large, comprehensive scheme such as that described in the paper, they are extremely remunerative.

Mr. T. S. Pick: Can the author give any further information as to the performance of the mercury-arc rectifiers which have been in service since 1923? Very interesting data should now be available as to the maintenance costs, and advantages over other equipment, especially rotary convertors.

It is interesting to note from the paper that the French railways are abandoning single-unit substations, the reason given being the small capacity of the unit installed in those substations. Does that reason still hold now that 2 000-kW units are available, or is there some other motive for abandoning single-unit substations?

The author states that the high-voltage connections are made manually, one man doing this service. Does that man work shifts, or does he man the substation over the whole 24 hours? What other work does he carry out during his turn of duty?

I should be glad of some information as regards the advantage of 6-phase double units over 12-phase units. Is this advantage due to the fact that the 12-phase units really function as 6-phase units on heavy load?

With regard to the polarized anode grids; do these anode grids remain permanently polarized, or are they polarized through relays when the current rises to a certain value.

I should also like to know whether the grid-controlled rectifiers cause any trouble with industrial supplies, or interference with communication circuits?

With regard to the section gaps, and particularly the intermediate sectionalizing stations, is any provision made for feeding through from one substation to another, and, if so, are any relays provided there so as to prevent overheating of the conductor due to rather small overloads persisting for long durations?

On page 234 the author mentions that the convertors have a compound characteristic, but later in the paper, when dealing with gradients, he says that the convertors must be capable of regeneration. Perhaps he would explain whether he has installed compound machines on the gradient sections.

Mr. H. C. Harris: Under the heading "Substations" it is stated that each convertor unit is protected against short-circuit on the direct-current side by high-speed circuit-breakers. Does the term "convertor unit" as used here include rectifiers? The usual practice is for the rectifier high-speed circuit-breakers to open on reverse current only as a protection against arc-backs, and for overload protection to be given by the circuit-breakers on the d.c. feeders. In the case where polarized grids are used, however, it would seem to make the use of reverse-current high-speed circuit-breakers entirely unnecessary.

Under the heading "Line Equipment" it is stated that there are no pull-offs on curves on the Midi Railway. This practice would appear to require an unnecessarily large number of supporting structures, and the hangers apparently exert a sideways pull in addition to supporting the contact wire vertically. The hangers, in fact, are really no longer hangers but a combination of hanger and pull-off. It would also seem that it would be difficult to adjust the position of the contact wire in a horizontal plane without causing variations in its height.

Reference is made in the paper to air-gap sectionalizing. Does this consist of overlap spans? In this case, the contact wires of two adjacent sections are run side by side for one span, each being terminated higher than the normal height so that one is gradually raised away from the pantograph, while the other is gradually lowered into contact, thus eliminating any arcing due to a momentary break in the circuit.

What methods are used for maintaining correct tension in the contact wires at all seasons, and how are they lubricated? Figures showing what wear has been experienced in the contact wires, and also a description of the type of pantograph finally standardized, would be useful.

Are supporting poles bonded to the tracks to prevent their becoming alive in the event of an insulator failure? If so, has any trouble been caused by traction current flowing through the bonds to earth causing erosion of holding-down bolts and cracking the foundations? This can be prevented by connecting spark-gaps, which will break down at about 200 volts, in series with the bonds.

What is the physical arrangement of the armatures in the experimental 3-armature motor to which reference is made? It is stated that the majority of locomotives have three different methods of coupling the motors, to enable them to be used for either passenger or freight trains. How is provision made for this?

Mr. F. V. G. Bird (*communicated*): Having spent 7 months on the Paris–Orléans and Midi Railways during 1936 as a student, I should like to give a few figures showing the excellent results obtained on this electric system, results which would not be obtained by any other form of traction.

Firstly, dealing with locomotive performance, Fig. A shows an acceleration graph traced from a Teloc record of a run of a 2–D–2 express locomotive (E.522), of 3 900 h.p. on the 1-hour rating, starting from Blois in the Tours direction and hauling a load of 11 steel coaches weighing 534 metric tons. It will be noted that the maximum permitted speed of 130 km.p.h. is reached from rest in 7·4 km. The starting current was approximately 650 amperes per motor on each starting connection. On this trip, the journey from Blois to Tours was run in 25 minutes at an average speed of 127·8 km.p.h. for an average specific consumption of 24·2 watt-hours per tonne-km. train (19·1 watt-hours per tonne-km. total). This train was regaining time lost by a signalling defect.

The following reading gives an idea of how great the sustained output can be when necessary. A 2–D–2 locomotive (E.704) hauling 16 bogies weighing 689 metric tons, was accelerated from the speed-reduction to 90 km.p.h. at Étampes to 105 km.p.h. on the Rampe d'Étampes, an adverse grade of 0·8 % about 7 km. long. To do this, 3 000 amperes were drawn from the trolley at 1 350 volts, an input of 4 050 kW. From the motor characteristics taken on test, the approximate horse-power developed was 5 040. Loads up to 972 metric tons (trailing) have been handled on the level at 120 km.p.h.

I will now give a few figures showing the maintenance economies which have been found possible.*

Express locomotives have a complete overhaul after approximately every 200 000 km. Actually, up to 230 000 km. has been reached in isolated cases, but further increase in this direction is limited by tyre wear. For an overhaul of the standard 2–D–2 E.500 class of locomotive about 3 300 man-hours are required, entailing an approximate cost of 55 000 francs. The work takes 15 days to carry out, and the cost quoted includes all materials required for the job. Overhauls of the new E.700 and E.4800 classes, having quill drives instead of the Buchli system, are expected to take approximately one-third more time than the E.500 class; then (1936) they were taking even more. The B–B locomotives and M–U stock have an intermediate overhaul between each main overhaul; the intermediate overhaul being made after 75 000 km. and taking 3 days in all cases, and the main overhaul after 150 000 km. and taking 6 days. Specimen times and costs are as follows:—

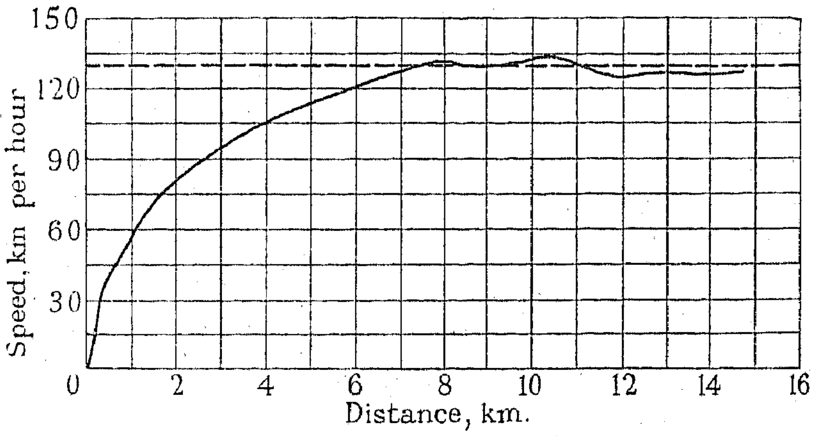

Fig. A

	Total man-hours	Cost, in francs (includes materials)
Main overhaul		
B–B (E.173)	1 133	29 882
M–U car (Z.176)	986	18 280
Intermediate overhaul		
B–B (E.144)	551	12 404
M–U car (Z.156)	286	5 391

Very efficient use is also made both of the locomotives and of the driving personnel. For example, referring to the Paris depot, the average distance covered in the summer by the express locomotives is 22 000 km. per month and the longest daily distance run by a single locomotive is 1 232 km. The drivers average, in summer, 11 000 km. per month. It is to be noted that they only carry out a brief check-over before starting their runs, all lubrication and maintenance duties being performed by a specialist staff. All wasteful waiting-about by the driving personnel is thus eliminated. It is to be noted that after being lubricated the express locomotives are designed to travel about 1 000 km. without requiring further attention, so that it will be feasible for the same locomotive to run right through from Paris to Hendaye on the Spanish frontier.

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* Costs refer to 1936 (75 francs to the £, approximately).

Oil consumption is very low. The figures, in litres per 1 000 km., are as follows:—

2–D–2, E.500 class	16·5
2–D–2, E.4800 class	11·3
B–B, E.1–170 classes	4·3
B–B, E.4501 class	3·6
M–U cars	4·23

Roller bearings are not used in any of the classes listed above, except on the bogie axle-bearings of E.4807.

In conclusion, I will give some figures showing the excellent workmanship put into these locomotives. Express locomotives E.501 and E.502, delivered in 1926, have each completed about 2 000 000 km.; and, of the 16 ring-lubricated main motor bearings originally fitted, 12 are still in use and only show wear varying from 0·1 to 0·3 mm. These motors are each of 930 h.p., 1 350 volts, on the 1-hour rating.

Mr. R. S. Blackledge (*communicated*): The author mentions the successful attempts of the engineers of the Paris–Orléans Railway to increase the power and efficiency of their steam locomotives: quite rightly does he do so. It is not too much to say that the well-known Compound Pacific class of that Railway has a power/weight ratio that is unequalled.

There are one or two questions that I should like to ask in connection with the section on "Locomotives and Motor-Coaches."

With regard to the nosing of the Paris–Orléans and Midi B_0–B_0 type locomotives, will the author tell us something more about the degree of rigidity that it was necessary to introduce between trucks in order to cure the nosing, and whether this involved any appreciable increase in the radius of the minimum traversing curvature. It would be of interest if he gave the wheelbase of the bogies, the distance between bogie centres, and the approximate value of the unsprung mass per bogie.

In connection with regenerative braking on the steep sections (1 in 50 and 1 in 100), he states that the high-voltage sides of the substations feed back to the network; will he tell us the amount of reverse-current protection that is provided on the d.c. side of the rotary convertors and synchronous motor-generators? Taking the case of a 700-ton train descending a 2 % gradient at a controlled and uniform speed of 60 m.p.h., the total braking power will be of the order of 3 500 h.p.; I assume that at times when the whole of the regenerated power must pass through the substation such an amount would be excessive. Is the motorman instructed as to the maximum amount of regenerated current that he must excite for, and to the effect that any heavier retardation must be accomplished by means of the continuous brake?

Mr. A. Bachellery (*in reply*): In France the most important factor in the electrification of a railway line is not the steepness of the gradients but the amount of coal to be saved. The most recent electrifications of French railways are on lines with gradients not exceeding 1 in 120.

It is difficult to compare the cost of coal with that of electric power in relation to railway traction, as the cost of current is very different according to whether it is measured at the power station or on the locomotives. In the paper the comparative costs of steam and electric traction are on the basis of the cost of current being taken at the point where it is fed into the 60-kV or 90-kV lines, and therefore including part of the cost of transmission and transformation.

The capital invested in electric locomotives has not been included in this comparison, because it is considered that if no electrification work had been done a similar sum would have been spent on the renewal of the steam locomotives during the last 15 years.

On the Paris–Orléans and Midi Railways, owing to the different sources of economy that I have mentioned, the cost of the crews' wages on electric locomotives is about half of that on steam locomotives for the same run. The gain of one man is generally obtained by dispensing with the fireman and placing the guard on the locomotive in his stead. On fast passenger trains, however, such as those between Paris and Brive to which reference has been made, a normal locomotive crew, including a driver and his assistant, has been maintained.

Multiple-unit trains have not yet been employed for minor long-distance passenger service, because the building of a costly rolling stock specialized for this service has not been thought advisable.

On electrified lines most of the yards and sidings are electrified, but ordinary 2-truck locomotives are generally used there at present, which explains the small number of special shunting engines.

The three different modes of couplings on B_0–B_0 locomotives consist of series, series-parallel, and parallel connections of the four motors. With this, and additional field tappings, a wide range of speed regulation can be obtained.

On the experimental 2–D_0–2 locomotive with 3 armature motors there is one such motor for each pair of driving axles. The quill on each axle is driven by one of the armatures through an ordinary pinion and gear drive; and the third armature's pinion drives both the quills through an intermediate gear.

The rigidity to be introduced in the coupling between trucks on the B_0–B_0 locomotives depends on the nature of the line and on the speed. It is, in fact, a compromise between two opposed requirements, both of which are of great importance in preventing fatigue and wear of the track, i.e. the suppression of nosing on straight sections and sufficient flexibility for taking curves. On mountain lines with very sharp curves a relatively loose coupling is necessary, whereas on flat lines with large radii of curvature where the permissible speed is higher, a stiffer coupling is called for.

The wheelbase of a bogie on these machines varies from 2·7 to 2·95 metres, and the distance between bogie-centres from 5·55 to 6·1 metres. The unsprung mass per bogie is approximately 10 tons.

Each substation is practically always equipped with at least two convertor units, principally for safety. These units, when of the rotary type, comprise two 750-volt machines in series; the individual 1 500-volt rotary convertor has not been developed, for the reason I have stated.

As to mercury rectifiers, the early type, consisting of two 6-anode tanks placed side by side and fed alternately by a single 12-phase transformer, has been replaced by separate 6-phase rectifiers, each having its individual transformer. The main advantage of this is that 12-phase transformers are very complicated and costly.

The anode grids on the rectifiers are permanently polarized. When a short-circuit occurs, however, the potential is altered automatically by means of a special relay. Where these grids are used, the rectifier high-speed circuit-breaker opens only on reverse current. It has not been considered advisable to suppress it entirely, especially where several rectifiers are used in parallel.

On sections where regenerative braking is used, the substations are equipped with rotary convertors. A special relay is provided to change the excitation from compound to shunt when the current is reversed. No difficulties ever arise in these substations from excess of reverse current. The power returned to the a.c. lines is always far less than that which the same substation has to draw out when supplying on the d.c. side. Part of the regenerated current is taken by other trains on the line, and part is absorbed in the losses. The drivers have instructions, however, not to allow the regenerated current to rise beyond a certain limit.

In the event of trouble it is always possible to run the line with one substation out of operation, and even in that case no overheating of the contact-wire has been noticed.

The attendant in charge of an automatic substation resides in the substation, and a bell signal gives him warning if anything goes wrong. In addition to operating the high-tension switching apparatus, his work consists mainly of cleaning and small maintenance operations. It seems, however, that this method of working will not be allowed under the new regulations.

In the Midi catenary construction (which is derived from certain American types) the hangers in the curves exert a sideways pull; but this does not imply a larger number of supports. In fact, for a similar degree of curvature the distance between supports is shorter on the Paris–Orléans than on the Midi lines.

On the Midi lines, the height of the contact-wire on curves varies slightly with the tension, but this variation does not give any trouble.

Turnbuckles are provided at each anchorage for the regulation of the tension in the catenary. In practice it is sufficient to adjust this twice a year at changes of seasons.

Lubrication of the contact-wire is obtained by greasing the current-collecting apparatus. The wear on the contact-wire depends principally on the amount of sparking. It may be relatively rapid on particular points where sparking is frequent, such as switches or crossings under bridges. It is more rapid on sections where steam locomotives normally run. Apart from these circumstances, however, it seems that the contact-wire (this being assumed to be worn out when its section is reduced by one-third) will last a minimum of 20 to 25 years under the heaviest traffic.

Air-gap sectioning is carried out by means of overlapping spans, the contact-wires of two adjacent sections being run side by side for one span.

The principal feature of the standard Paris–Orléans and Midi pantograph is its head, which consists of a horizontal frame articulated on the top bar. This frame carries the current-collecting device composed of two steel pans, each of which rests on four helical springs. On each pan are fixed three copper strips for current collection; the high flexibility of the springs allows these strips to keep in perfect contact with the wire. Bonds of copper cable connect the pans to the main structure of the pantograph, the joints of which are provided with ball bearings and are also copper bonded.

The steel supports of the catenary are earthed at regular intervals. The most reliable method is to connect them to the track; but this cannot be done on lines where automatic signalling is used, on account of the possibility of incorrect operation of the signals in the event of failure of an insulator. Where the supports are bonded to the track, no erosion of the foundations due to leakage of the track current has been noticed. In a few instances, however, a short-circuit on a catenary support where the bonding was defective started an arc between bond and rail, which resulted in serious damage to the latter. These bonds must therefore be frequently inspected.

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 15TH NOVEMBER, 1937

Mr. Joshua Shaw: The Paris–Orléans and Midi Railways have the following remarkable features favourable to electrification which no railway in this country possesses: (1) The electrification covers a great number of mountain routes, some with gradients of 1 in 25, and also other routes carrying dense traffic. (2) The Railways have a plentiful supply of water power. (3) The Railways have the right to supply electricity from their generating stations and from their transmission lines for industrial purposes. (British railway companies would have to buy electricity from outside sources if they proceeded with electrification.)

In this country the absence of these three factors is a great bar to the progress that might be made with railway electrification. We have many sections of railway which could with advantage be electrified, but I am afraid it will be many years before any scheme to electrify all our main-line railways will be carried out.

One of the points in which I am particularly interested is the economy of fuel consumption derived from electric traction on the author's mountain and other lines with very heavy gradients. I have compared his figures in this connection with some obtained on the Mersey Railway, which has gradients of 1 in 35, 1 in 30, and 1 in 27, and have found that electrification led to a saving in fuel cost per ton-mile of 48 % as compared with steam operation. This figure was obtained at the time when reciprocating generating sets were in use, and the more modern turbo generating sets now employed have increased the saving to about 78 %. I have compared these results with the author's statement "The average economy of coal on these companies' electrified lines is roughly

400 metric tons per kilometre of route, which is generally admitted to warrant the cost of electrically equipping the permanent way"; according to my calculations this figure of 400 metric tons per kilometre of route corresponds to an economy of about 35½ % on steam operation, which seems a fairly low saving to warrant electrification.

The author states that the total reduction in operating expenses on his system in 1936, due to electric traction, was 125 million francs, representing approximately 7 % of the capital invested in permanent-way electric equipment. I am not quite sure why he quotes this saving in terms of the capital invested in permanent-way equipment only, but it may be that some portion of the expenditure applies to generating plant for industrial purposes other than the railway. Expressed in terms of the whole of the capital expended (3 730 million francs) the saving is only 3·4 %. Comparing these actual savings on the Paris–Orléans and Midi Railways with the saving estimated to accrue on the electrificaton of the British railways, the Weir Report of 1931 stated that on a capital expenditure of £261 000 000 the saving due to electrification would be approximately £17 500 000, or 6·7 % of the capital expenditure. (The figure for capital expenditure does not include the cost of generating plant, because current would be supplied from an outside source.) The Report made the comment that such a return would not warrant the adoption of general electrification. Excluding capital expenditure on generating plant from the figures for the Paris–Orléans and Midi Railways, we obtain a saving of 4 % to be compared with the 6·7 % estimated for the British railways. Expressing the savings as a percentage of the capital expenditure in respect of permanent-way electric equipment only, the French and British figures are 7 % and 10·4 % respectively. These results are surprising, because with their supply of water power the French should theoretically be able to save much more in working expenses than the British railways could hope to do. It should, however, be remembered that the figures quoted in the Weir Report are only estimates, whereas those for the Paris–Orléans and Midi Railways represent actual working results.

The object of electrification is not only to obtain a reduction of working expenses but to increase the net revenue of the undertaking, a point which my own experience on the Mersey Railway emphasizes very forcibly. When the electric service was introduced it did not save one penny on working expenses; in fact, the expenses were increased by 7½ % because a more extensive train service was introduced than could possibly have been worked by steam traction. Nevertheless, electric traction has enabled the traffic to be developed to such an extent that the present-day increase in net revenue alone is approximately 20 % of the capital that was invested in the electric installation.

It is interesting to note that in the Weir Report the cost of track equipment and locomotives for all British railways is given as 64·5 % of the total, compared with the author's figure of 65·6 % for the Paris–Orléans and Midi Railways; while for the cost of locomotives the figures are 35·5 % and 34·4 % respectively.

Prof. F. J. Teago: It is interesting to note that, having tried out both the third-rail low-voltage d.c. system and the overhead high-voltage single-phase system, the French railways have standardized the overhead 1 500-volt d.c. system throughout the country.

The author mentions that, with the exception of shunting duties, the whole of the main-line services are operated with two classes of locomotive, a 2–D_0–2 for express work and a B_0–B_0 for freight and stopping trains: this should ease operation and reduce costs.

I should like to know whether it is thought feasible to work the 130-mile Paris–Le Mans section with motor-coach stock, or whether it is felt essential to have locomotives for this run; it was, I believe, intended to use motor-coach stock as far as Chartres.

Can the author tell me whether the cost of the mercury-arc plant necessary to effect regeneration has been the bar to its use, or whether technical operating difficulties are anticipated? His experience bears out the belief that one electric locomotive can do the work of two steam locomotives, and he stresses the point that only men of exceptional physique can stand the strain of firing a modern 2 500-h.p. steam locomotive on a long run. I am glad that full recognition has been given to the fact that increased speed must be attained if the severe competition of road transport is to be met, and that to this end 15 % has been cut off the time of run between Paris and Brive, a distance of 310 miles. In these days of rapidly-changing values, importance must be given to the author's observation that in the case of electric traction, as labour costs are a lower proportion of the total cost of transport, the adverse effect of rising wages and shorter hours is less than in the case of steam traction.

Mr. H. W. H. Richards: It would be interesting if the author could state the average cost of locomotive coal, including transport and handling, on important sections of the Paris–Orléans and Midi Railways before electrification took place.

He points out that the use of the 1 500-volt d.c. system on the Paris–Orléans and Midi Railways fits in conveniently with the general electricity-generation practice of the country, namely 3-phase alternating current at 50 cycles per sec. It has been suggested that in this country the cost of electrification could be reduced by the use of direct current at 3 000 volts, or alternating current at even higher voltages; but this saving is doubtful, as the average distance between railway junctions in England is approximately 15 miles, and the average distance between stations is 2·35 miles. The location of substations is governed largely by geographical conditions, and the relatively short distance between stations would probably require a large proportion of multiple-unit trains for passenger services; and the 1 500-volt equipment has many financial and other advantages over the 3 000-volt equipment for motor-coach purposes. It would be interesting to know whether, if electrification were now being commenced on the author's system, the geographical conditions in France would cause serious consideration to be given to the 3 000-volt d.c. system.

In view of the recent development of high-speed trains in England, it is interesting to learn that both the weight and the speed of trains are increasing in France, and that in the case of the Paris–Orléans and Midi Railways the use of electric traction is of material assistance for this purpose.

I should like to refer to the position of railway electrification in relation to war conditions. As regards the supply of power, a large proportion of industry and the general amenities of life are now supplied by a limited number of interlinked power stations, a system which has certain risks but also certain facilities due to its interconnections, so that the electrification of railways would not appear to be worse off than other conditions of modern life in this respect. Past experience with the maintenance of the overhead-line equipment on the suburban lines of the old London, Brighton and South Coast Railway running into two important terminal stations—London Bridge and Victoria—indicates that when accidents or special civil engineering work, such as the replacement of steel bridges, takes place, very little time is required for dealing with the necessary alterations to the overhead-line equipment. Therefore, if an aerial attack resulted in damage to a railway line, the delay should not be materially increased if electric traction were more widely used. As mentioned in the Weir Report it would, however, obviously be desirable for a reserve of steam or other self-contained locomotives to be retained for dealing with possible war-time conditions.

Mr. G. H. Fletcher: In 1928 a considerable amount of trouble due to high-voltage surges was being experienced on the Midi Railway, the surge voltage amounting to 20 000–30 000 volts. Has this trouble been overcome, and, if so, in what way? Another trouble which was being experienced at that time was flashing-over on the commutators of the main motors. Certain modifications were made to these motors, and I believe the interpoles were adjusted, with the result that on many of the motors considerable improvements were obtained. The line was also temporarily sectionalized in order to reduce the trouble on the motors. Also, owing to shortage of labour and probably of money at that time, the track had been allowed to get into bad condition, and a good deal of work was done to improve it.

On the Paris–Orléans line, trouble with the flashing-over of motors at high speeds was partially overcome by the use of two pantographs instead of one.

I am interested to learn from the paper that no further locomotives of the vertical-motor type are being put into service. During a visit to the Midi Railway I rode on several of these locomotives and thought them to have particularly good riding characteristics, and to take the curves very well indeed. I note that the maintenance cost of this type of locomotive is rather high, and I should like to know whether this is because of the high maintenance costs of bevel gears.

I am interested to read under the heading "Substations" that motor-generator sets, rotary convertors, and rectifiers are used. Will the policy in future be to use only rectifiers? If so, there may be difficulties from the point of view of receptivity of current from the locomotives which are running regeneratively, but where it is possible to mix rotary-convertor and rectifier substations that problem can be very well overcome. Presumably the load is fairly heavy, and if there is always at least one train motoring whilst one is regenerating the problem of the receptivity of the line is not difficult to meet; but on main-line electrification with only one train every half hour or so, and with many sections of the line without load, the receptivity will be a rather difficult problem. Is this problem met in France by utilizing those substations which are equipped with motor-generators or rotary convertors, or are some other means also employed, such as resistances brought into operation by relays?

I should like to have the author's opinion of the portable substations used by the Italian State Railways. According to Mr. Bianchi, portable substations cost about half those built of brick or concrete, and their portability gives many advantages from the point of view of repairs, or extensions to meet exceptionally heavy conditions. Moreover, in the tunnels spaces are provided where these substations can be placed in time of war and thus be protected from aerial attack.

The author refers to the application of the Metadyne system for shunting service. We have been developing this for a number of years, and have recently fitted it to 52 units on the Underground Railways. It is very suitable for shunting service, where maximum utilization of available adhesion is required in the transmission of power. With this system, at the moment of starting the current taken from the overhead line is extremely small because there is no loss in resistances and the full voltage is simply transformed to a low voltage with the maximum current. Therefore, when the contact is stationary the current at the contact point is very low and there is no burning.

The data given by the author justify the decision arrived at in the Weir Report that 1 500 volts is a suitable voltage for railway electrification in countries such as Great Britain. Some years ago it appeared possible that designing engineers would have to consider voltages of 4 000, 5 000, or even 6 000 volts for d.c. traction, and they were quite prepared to meet that condition. The development of automatic substations, portable substations, and rectifiers during the last 10 years has, however, made it less necessary to adopt high voltages, and it is possible and economical to space the substation units along the line instead of having large units spaced infrequently, providing the load on the system is such that each individual unit on the line is of economical size.

Mr. A. Priestley: On page 235 the author states that on the 2–D_0–2 engines the control is electro-pneumatically operated. I understand that originally on the Midi Railway the control was by camshaft operation, and I should like to know why this method has since been abandoned. On some recent South African railway locomotives the cam-operated switch groups have been replaced by unit and drum switches, on account of the trouble which has occurred due to the contacts affecting the regeneration circuit. I notice that on the Paris–Orléans and Midi system there are 521 locomotives of the B_0–B_0 type; what type of control is used on these?

Mr. A. B. Washington: The 4-wheel B_0–B_0 type of locomotive has a total rating of between 1 400 and 1 800 h.p., or roughly 400 h.p. per motor; I suppose these motors weigh approximately 4 tons each, and perhaps the author could state the exact figure. These locomotives run at a maximum speed of 105 km.p.h., or roughly 65 m.p.h. It would be interesting to know whether the maintenance costs on the track have been found to be of a high order as the result of this combination of a heavy axle-hung motor and a fairly high speed. For instance, do the rail joints suffer very badly, or does the inside of the rail show marked wear due to flange action? It is mentioned in the paper that speeds of over 80 km.p.h. on this type of locomotive require special devices; perhaps the author could give us details of these.

Turning now to the high-speed types of locomotive, the 2–C_0–2 and the 2–D_0–2, where the speeds are higher and the motors are mounted in the body structure, these motors have a larger horse-power than those on the B_0–B_0 type and are presumably much heavier. Will the author confirm that the reason for departing from the use of the ordinary axle-hung motor in the case of these high-speed locomotives was simply to find physical accommodation for them, or was the type of drive changed because of the heavier motor and the higher speeds? The latter combination of factors might, with axle-hung motors, have seriously impaired the riding qualities of the locomotive or caused appreciably greater track maintenance.

I should be glad to know whether any of the overhead structures which support the overhead lines, or metal bridges, are earthed to the running rails; and also whether they have given any trouble due to electrolysis.

Have any tests been made to determine the train resistance of the multiple-unit and also the locomotive-hauled trains? If so, can the author give an indication of the results?

Mr. A. D. Ferguson: One of the difficulties which has been encountered in connection with railway electrification has been excessive wear of the overhead conductor, and I should like to ask the author what his experience of conductor wear has been and what measures, if any, he has taken to minimize it. Rather serious wear took place on the South African Railways, but I understand that it has now been reduced to an almost negligible value by the provision of lubricators which supply a slow but continuous feed of heavy oil to the surface of the collector shoe. Oil is contained in a small reservoir mounted on the pantograph frame and is fed to the collector shoe through flexible tubing, the oil being under air pressure and the rate of feed regulated to suit local conditions. In general, the rate of feed is adjusted to empty a 2-gallon reservoir in 2–3 weeks. This system has also been adopted on the recently-electrified section of the Central Railway of Brazil. I should like to ask the author whether he can give figures of the wear and the anticipated life of the overhead conductors on the Paris–Orléans and Midi system. It would also be interesting to know whether the wear is greater where heavy currents are collected, i.e. during acceleration and when ascending heavy grades, and less in places where coasting usually takes place.

I notice from the author's lantern slides that single-shoe pantographs are employed on some of the largest locomotives of 4 000 h.p. Are both pantographs continuously in use? It would appear incredible that one pantograph could collect the whole of the current. Single-shoe pantographs have become very common in recent years, and are capable of collecting as much current as the old double-shoe type; because, in the case of the old type, owing to the method of suspension usually adopted, the leading shoe acquired most of the pressure and therefore collected most of the current. I should like to have the benefit of the author's experience in regard to the pressure between the collector shoe and the overhead wire, as this undoubtedly has a great influence on wear.

Is any provision made for surge-voltage protection on the locomotives and overhead lines of the author's system? In my experience it is difficult to obtain protective apparatus for locomotives which is sufficiently compact and on which little maintenance work is necessary. In view of these difficulties, there is at the present time a tendency to dispense with such apparatus.

Mr. R. Varley: It would be interesting to know which type of mercury-arc rectifier has been adopted on the author's system—the metal-tank or the glass-bulb type? The glass-bulb type seems to be gaining favour in this country.

How long has the Metadyne system been in use on the Paris–Orléans and Midi Railway? This system of control is only in its infancy so far as Great Britain is concerned.

I have seen some very severe thunderstorms in the South of France, and I should therefore like to ask whether much damage has been done to the author's overhead lines by lightning.

The financial results recorded in the paper are very interesting and support the experience of the Southern Railway in this country.

Mr. R. A. S. Thwaites: In the case of the Paris–Orléans and Midi Railways, 5 524 km., or about 3 500 miles, of track have been electrified. This compares with a total length of electrified track in this country of about 2 000 miles, of which the Southern Railway have electrified about 1 370 miles. It is interesting to note that the annual consumption of 470 million units given in the paper is within a few per cent of the annual consumption of the Southern Railway, which is approximately 450 million units.

With reference to the author's statement that "protection against voltage surges is provided on the high-voltage as well as the low-voltage side through various types of lightning arresters, inductive coils, or shunted condensers," would the author be good enough to tell us a little more about the type of protection which he has found to be most satisfactory?

Although the thermal efficiency of steam locomotives has increased from 3 % to between 5 % and 6 % in the last few years, a large modern generating station has a thermal efficiency of about 30 %, and an effort certainly ought to be made to conserve our fuel resources in the interest of future generations.

Mr. G. W. Parkin: A technical point which strikes me as interesting is the utilization for shunting purposes on the 1 500-volt overhead lines of 600-volt locomotives formerly running on the Paris suburban section, by the replacement of the original control equipment with convertors supplying current at varying voltage on the Metadyne system. This procedure, apart from giving a new lease of life to equipment which otherwise would be defunct, has presumably also eliminated all rheostatic losses, which are generally of considerable magnitude in this class of locomotive.

Electric traction on the Paris–Orléans Railway dates from 1900, when the underground suburban lines terminating at the Quai d'Orsay station, Paris, were electrified. This was the first instance in Europe of electric traction supplanting steam. This 600-volt third-rail section has now been re-equipped on the standard system, and I should be pleased if the author could say whether the overhead system has proved as reliable as the third-rail system for dealing with dense traffic in tunnels, where presumably inspection of overhead equipment and contact-wire renewals can only be carried out during the hours when there is no traffic.

Previous speakers have commented on the slow progress being made with railway electrification in this country. Perhaps we should remember that Great Britain is the birthplace of the steam locomotive and that our national asset, coal, has to be hauled no great distance to any of the locomotive refuelling depots. I understand that the savings which, according to the Weir Report, would be effected by electrification have already been realized by steam operation, chiefly through more efficient steam-locomotive working. Mr. Richards has already commented on the vulnerability of electrified lines in the event of war, and it would appear that, especially for the operation of military railways, a reserve of steam locomotives should be maintained for the purpose of train haulage by prime movers.

Nevertheless, there are many zones where electrification would increase the railway companies' net revenue, and it is hoped that the electrification schemes now being actively pursued will prove that there is ample scope for further ventures.

Mr. O. J. Crompton: On page 235 it is stated that the Paris–Orléans type of pantograph gave trouble at high speeds on the Midi lines, and vice versa. I should be glad to know whether this trouble was due to varying pantograph pressures, varying contours of the pantograph, or some feature of the overhead equipment itself.

My second point concerns the running of trains from live sections into dead sections. Outside each substation there are overlap spans between separately-fed equipments running in each direction. If a train is running along a live section and if there has been an overload on the next section which has brought out the substation circuit-breaker, the train on entering the overlap span will bridge the live and the switched-out sections with its pantograph. As the train leaves the overlap span, the full-load current of the train will be broken at the pantograph as it leaves the live contact wire. This may cause severe damage to the contact wire and the catenaries. Trouble may occur similarly at section insulators as well as at air-gap overlap spans. From the author's slides I gather that the section insulators are of the wood-break, continuous-feed type, which would, I think, be rather vulnerable. I have on two occasions seen overhead equipment burnt through and brought on to the track in this way, though the d.c. line voltage in these cases was 3 000 volts and not 1 500 volts as on the French railways.

The risk of this happening is greatest when the railway has been recently electrified and the feeder circuit-breakers are being fairly frequently brought out by teething troubles in the substation gear, the locomotives, or the overhead equipment. When the equipment has settled down, the risk is much more remote. But, however remote the risk of such an occurrence, the consequences may obviously be very serious, and I have heard of serious trouble of this sort in three different countries during the last few months. Are any special steps taken on the French railways to prevent a train from running into a switched-out section?

Mr. R. C. Smith: Electric traction is sometimes said to be very vulnerable in time of war; but I feel that too much is often made of this point, because if an air raider were to make a good hit on such a place as the Welwyn Viaduct or the Runcorn Bridge it would not matter whether the railway was electrified or not. I understand that there has been no electrification of the French railways east of Paris, and perhaps the author would explain the reason for this.

It would be interesting to know whether the author has considered the use of glass-bulb rectifiers on his system, because in this country the London, Midland and Scottish Railway have installed a number of these, and so far they have been quite successful.

In the paper it is mentioned that the high-voltage switches at the substations are manually operated, there being one man in each substation. It seems strange that when the major portion of the apparatus in the substation is remote-controlled, the author does not so control the whole of it, thus having only one attendant for half-dozen or more substations instead of for each substation.

As regards track equipment, it would be interesting to know what the experience has been on the Midi line as regards cost of maintenance of conductor rails on the one hand and of the overhead-contact system on the other, as this line has had the advantage of experience of both types.

Mr. O. I. Butler: Whilst Metadyne control is not as simple and straightforward as series-resistance control, its performance in regard to saving of energy and facility in manœuvring is exceedingly good. It is usual to find that the more complex the system the greater are the maintenance costs, and I should like to know the extent of increase in maintenance costs incurred by the use of the Metadyne system. A study of the Metadyne indicates that commutation is rather more difficult than with the ordinary d.c. motor or generator. I should like to know whether this has been at all evident in the operation of the Metadyne on the Paris–Orléans locomotives.

Lieut.-Col. H. E. O'Brien (*communicated*): Those engineers who have been believers, on what they considered to be the soundest engineering and economic grounds, in the application of electric traction to lines carrying traffic above a certain density, have long been at a disadvantage in that the predicted economies could only be estimates: estimates based on very sound data it is true, but when companies are asked to spend many millions on revising and making alterations to methods of working which are the results of many decades of experience and which have become ingrained in the staff, alterations which may also raise grave social problems, it is not unnatural to find a tendency to hang back and wait. The figures given by the author seem to indicate broadly that suitable future electrifications, which can derive the full benefit of the experience of such companies as the Paris–

Orléans, should prove to be substantially economic propositions.

The physical characteristics of the railways in densely-populated countries (these necessarily being the most suitable for electrification on account of the density of traffic) prohibit high average speeds on account of the low accelerations obtainable with the steam locomotive, with its limited tractive effort. If the demand for increased speed is fostered by the provision that has already been made for such increased speed by the use of streamlined trains for long distances, it is difficult to see how a general acceleration of services can be met without the electrification of those portions of the line carrying a dense traffic.

In view of the increased efficiency that is being obtained from the steam locomotive and the progress that is being made in the design of Diesel engines, it is evident that in future every effort will have to be made to cut down the capital and operating costs of electrification. Standardization from the outset will effect a substantial reduction over past prime costs. It was clear some years ago that, given certain further modifications in designs that were then being brought out by the more progressive manufacturers, both here and on the Continent, the maintenance costs of both suburban motor-coaches and main-line electric locomotives should be reducible to a fraction of those of steam or Diesel-electric locomotives. I should be glad if the author could give some figures on this aspect of the problem.

It would be interesting to know, in more detail, how the shunting problem has been solved. Presumably all sidings have been electrified; if so, has it been possible to design a specially inexpensive overhead equipment for this purpose?

It is evident that, where locomotives can operate for 1 000 hours or more without cleaning or attention and where there is interchangeability between freight and passenger locomotives, a new operating technique is required both in the locomotive running and traffic departments, particularly if standardization has been thoroughly carried out.

This is a side of electrification on which little or nothing has been written hitherto and which demands more attention in the future.

It has always seemed desirable, with a view to one-man operation, that it should eventually be possible to keep every driver and guard in telephonic touch with the nearest signal-box, or that the safety handle on the controller could be made to give a visual indication in the signal boxes on each side of the train. Whether such a refinement would really be worth while is open to argument, but in due course it might enable substantial economies to be effected.

I should like to know whether, in the case of the Paris–Brive expresses, corridor communication with the locomotive from the train enables the driver to be relieved during a run of so long a duration as 6 hours.

I regret that the paper is not accompanied by a map of the whole network of the Paris–Orléans and Midi Railways, showing which lines have been electrified.

The relation of the traffic on those lines not electrified to those electrified is important, and more than one promising main-line electrification has been found economically impracticable because of the large mileage of unremunerative branch lines which it would have been necessary to electrify to make a complete scheme: the Diesel-electric locomotive will, however, eventually at least partly solve this problem.

Mr. A. Bachellery (*in reply*): I think it is impossible to compare the electrification of an extensive system of railway lines with that of a suburban line such as the Mersey Railway. In the latter the chief object of electrification is to cope with a growth of traffic that has exceeded the technical possibilities of steam traction; consequently, a large increase in receipts is to be expected. On main lines, where the traffic is relatively stabilized, the real problem is to retain it against various competitors, and to increase the net revenue by cutting down the working expenses.

There is no doubt that on the Paris–Orléans and Midi lines electric traction has been of assistance in preventing loss of traffic, and this ought to be placed to the credit of electrification, if it were possible to state it in figures.

The price of locomotive coal at the time electrification was started on the various Paris–Orléans and Midi lines has no real significance, in view of the several changes that have taken place in monetary units during the last 15 years. I can state, however, that in 1936 the cost of locomotive coal for steam traction was 11·8 per cent higher than that of the electrical energy corresponding to the same amount of work done on electrified lines, the cost of the current being taken at the point where it is fed into the 60-kV or 90-kV lines.

At the present time, the Paris–Orléans and Midi Railways have no mercury rectifiers arranged for the conversion of direct current into alternating current where the locomotives run regeneratively. This is not only because such rectifiers are costly, but also because it seems advisable to wait for further experience regarding their reliability. There are instances of the use of both rectifier and rotary-convertor substations on lines where regenerative braking is employed, and no difficulty has been experienced; but the regenerated current is always received in rotating convertors.

All the mercury rectifiers in use on the Paris–Orléans and Midi Railways are of the steel-tank type. No glass-bulb rectifiers have been tried. Neither have they any portable substations, but it is proposed to experiment with some stations of this type.

Inspection and maintenance of the overhead construction can be carried out without great difficulty, even inside the tunnels.

The wear of the contact wire depends essentially on the amount of sparking. The best means of preventing it is therefore to provide a good contact between the wire and the collecting shoe, and to eliminate all the causes of interruption of the contact, such as hard points, etc. The design of the pantograph must be closely adapted to that of the contact line. That is why a pantograph designed in connection with a special overhead construction is liable to give trouble on lines having a different equipment. The standard pantograph allowing collection on both the Midi and Paris–Orléans systems has two pans, each resting on four helical springs carried on a horizontal frame which is articulated on the top bar. In this way the pressure is equally distributed between the two pans, and the small inertia and large flexibility of the collecting shoe ensures permanent contact with the line even at high speeds. Only one pantograph is normally raised, and it is sufficient to collect the whole of the current.

Wooden section-insulators are used only on side tracks. On the main tracks, only air-gap sectionalizing is employed. Of course, arrangements must be made to prevent a train from bridging over a live and a dead section. For that purpose the French railways have two types of portable signals: one to order the driver to cut off the current on the locomotive, and the other to order him to lower the pantograph. In addition, in some cases a stop signal is set at the beginning of the defective section.

On the Midi lines some trouble has arisen owing to storms and high-voltage surges. As a result the insulator chains on the catenary have had to be reinforced in order to prevent failures. The flashing-over of locomotive motors due to the same cause has been effectively cured by improving the design of the motors.

To prevent the effects of lightning striking the line, which sometimes resulted in the simultaneous breakdown of several locomotives, all locomotives on the Midi Railway have been provided with lightning arresters, generally consisting of a condenser; this has proved to be a very valuable protection.

The high cost of maintenance of vertical-motor locomotives is due not so much to the bevel-gear drive as to the electrical equipment. Owing to clearance requirements, the twin vertical motors can have only very narrow rotors; this condition prevents a really satisfactory design and makes the motors susceptible to failure in case of overload.

The primitive camshaft control is still in existence on the first B_0–B_0 Midi locomotives. But this system, where the same circuit-breaker was used for control operation and for protection against overload, gave some trouble and had to be completed with a special quick-acting circuit-breaker. In the more recent series, the control is effected through contactors; these are driven, according to their function, either separately by electro-pneumatic valves, or in groups by a cam device.

The Metadyne system works very well on the Paris–Orléans shunting engines. But the short time these locomotives have been in service, and the particular work for which they are specialized, do not permit comparison of maintenance expenses with other systems of control.

On the average, the cost of maintenance of electric locomotives on the Paris–Orléans and Midi Railways is less than half that of steam locomotives for the same run.

As has been stated, the B_0–B_0 locomotives must not be allowed to attain too high a speed lest they put an excessive strain on the track owing to a large proportion of their weight being unsprung and also to their tendency to swivel. The special disposition adopted in order to allow them to run at over 80 km. per hour without damaging the track consists in coupling the two bogies together. This is done on the Midi locomotives by means of a drawbar and buffers; on the Paris–Orléans locomotives, however, where the tractive effort is transmitted through the main frame, an attachment has been fixed on the inner extremity of each bogie, and is connected with that on the other bogie by a spring which opposes lateral displacements. These devices have permitted the maximum speed of certain series to be raised to 105 km. per hour; but this is, I believe, a limit that could not be exceeded. That is why, in the design of high-speed types of electric locomotives capable of running up to 130 km. per hour, axle-hung motors have been replaced by entirely spring-borne motors.

THE SECOND PARSONS MEMORIAL LECTURE
"SCIENTIFIC ACTIVITIES OF THE LATE HON. SIR CHARLES A. PARSONS, O.M., K.C.B., F.R.S."

By GERALD STONEY, D.Sc., F.R.S., Member.

(LECTURE *delivered before* THE INSTITUTION *25th November*, 1937.)

PERSONAL RECOLLECTIONS

The fame of Sir Charles Parsons will always rest mainly on that part of his work which is best known to the public, namely the invention and development of the steam turbine. The genius, courage, and untiring energy which he devoted to the perfecting of this form of prime mover, and the revolution which he thereby accomplished in the production of power on land and sea, will always command both wonder and admiration. It was natural, therefore, that steam and steam turbines should have been chosen as the subject of the first Parsons Memorial Lecture, delivered last year by Sir Frank Smith. When I, as a lifelong friend and colleague of Sir Charles Parsons, was honoured by the invitation to deliver the second lecture of the series, I felt that as this aspect of his work had already been dealt with so ably, and so recently, I might more profitably devote myself to some of the less well known activities of the great engineer. I hope, in so doing, not only to show how wide were his interests, and how extensive his knowledge, but also to give some idea of the way in which he attained his results. To illustrate the latter I shall have occasion to make many references to his work on turbine machinery, as this filled so large a part of his life. I had the good fortune to be in the closest touch with Sir Charles during his most prolific period, from 25 to 50 years ago, and it is largely from my recollections of that time that the substance of this lecture has been drawn.

When quite a young man, in 1880 or perhaps even earlier, Parsons became interested in the production of power from the kinetic energy of a jet of gas, as an alternative to using the pressure of the gas on a piston. His first efforts in this direction were applied to the development of torpedoes, which were to be driven by the kinetic energy of the gases produced by the combustion of an explosive. Later on he turned his attention to the propulsion of vessels, and there is preserved at the Heaton Works a model of a boat the propeller of which is driven directly by the action of compressed air. This model is shown in Fig. 1 (see Plate 1, facing page 248). The propeller, as will be seen, is surrounded by a double shrouding carrying blades on which the jet of air impinged. It is evident that this work led up to the conception of the steam turbine, to the development of which his life was so largely devoted.

Parsons conceived the idea of the steam turbine by noticing the analogy between the flow of steam under small difference of pressure and the flow of an incompressible fluid like water. He has stated this himself, but he never told anyone, not even the most trusted members of his staff, how he arrived at the design in detail of an actual machine for any given conditions. That he possessed high mathematical ability is proved by the fact that he was Eleventh Wrangler in the Mathematical Tripos at Cambridge, but he was rarely, if ever, known to make use of formal mathematical reasoning for the solution of any problem. He had a thoroughly scientific mind and scientific habits of thought and his results were the outcome of these, rather than any deliberate calculations.

By analogy with the flow of water, Parsons realized that, for small differences of pressure, the velocity of steam escaping from a nozzle could be represented by an expression of the form $v^2 = 2gh$. For water, of course, h is the static head in feet. In steam, if H is the "homogeneous head" ($H = 144pV$), it follows that $h = Hdp/p$ and $v^2 = 2gHdp/p$. The great advantage of dealing with H in place of either pressure or volume is its relative constancy along a turbine. In a modern turbine the pressure may vary in the ratio of about 1 000 to 1, whereas the corresponding variation of H will only be about 2·5 to 1. In fact, in the early non-condensing turbines H only varied by about 15 %. Parsons certainly made much use of the function H, of which he was very fond, and it seems to me that the advantages of this function are not recognized as fully as they might be, in calculations relating to steam and other gases.

In the early days Parsons used to come into the drawing office with a scrap of paper on which were written particulars of the blading he had decided on for a certain machine. This was set out to scale, and modified if necessary according to his judgment. The staff were completely puzzled as to how he determined the proportions of the blading. It was not until turbines had been built for nearly 25 years that members of his staff evolved a sound theory of the steam turbine, and when Parsons was informed of this and had approved of it he was content to leave the design of the blading largely in their hands, though he continued to exercise the closest supervision over the details and general mechanical design. He realized most thoroughly that the first essential in a machine is that it should run properly and be reliable.

Parsons was never known to use a slide rule. He seemed to have no need for such a thing, as he could work out results in his head or on paper as quickly as most people could obtain them on a slide rule, though he never explained the process and it is doubtful if he could have done so. It never seemed to him that his

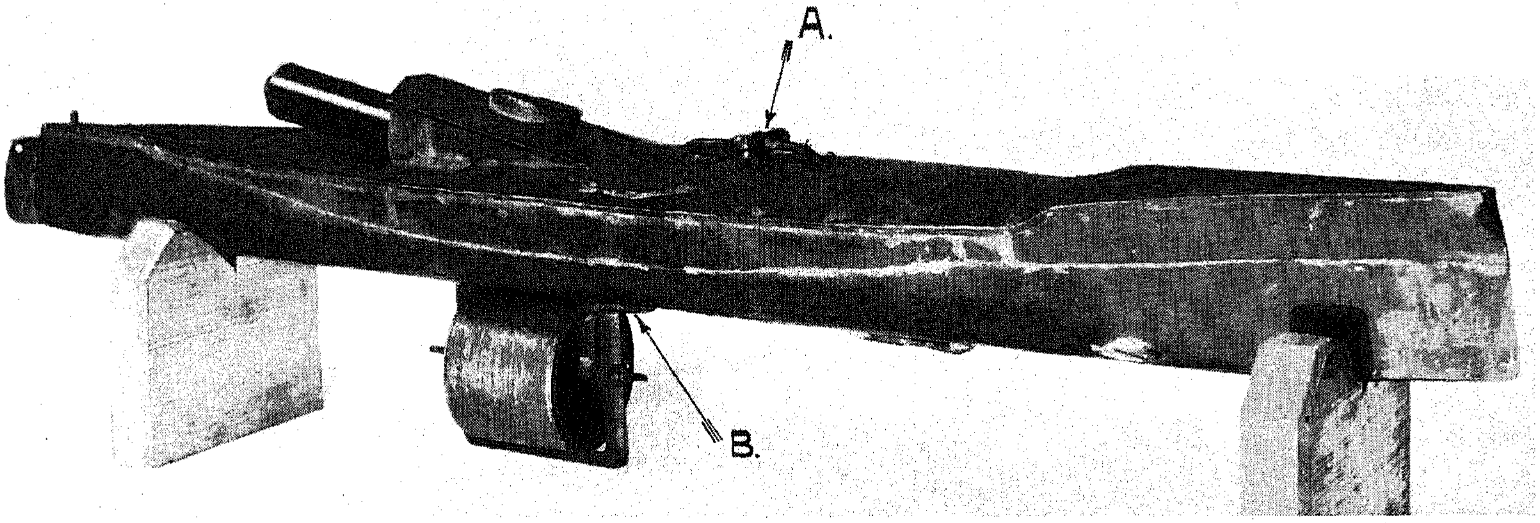

Fig. 1.—Model of a boat with compressed-air turbine and propeller underneath.

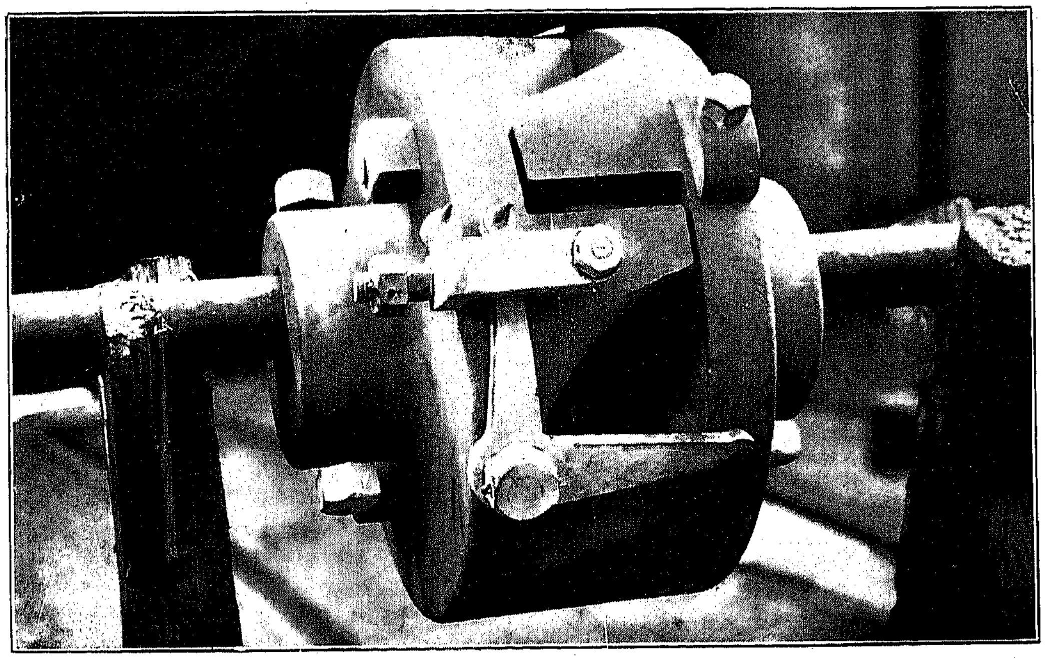

Fig. 8.—Torsion meter.

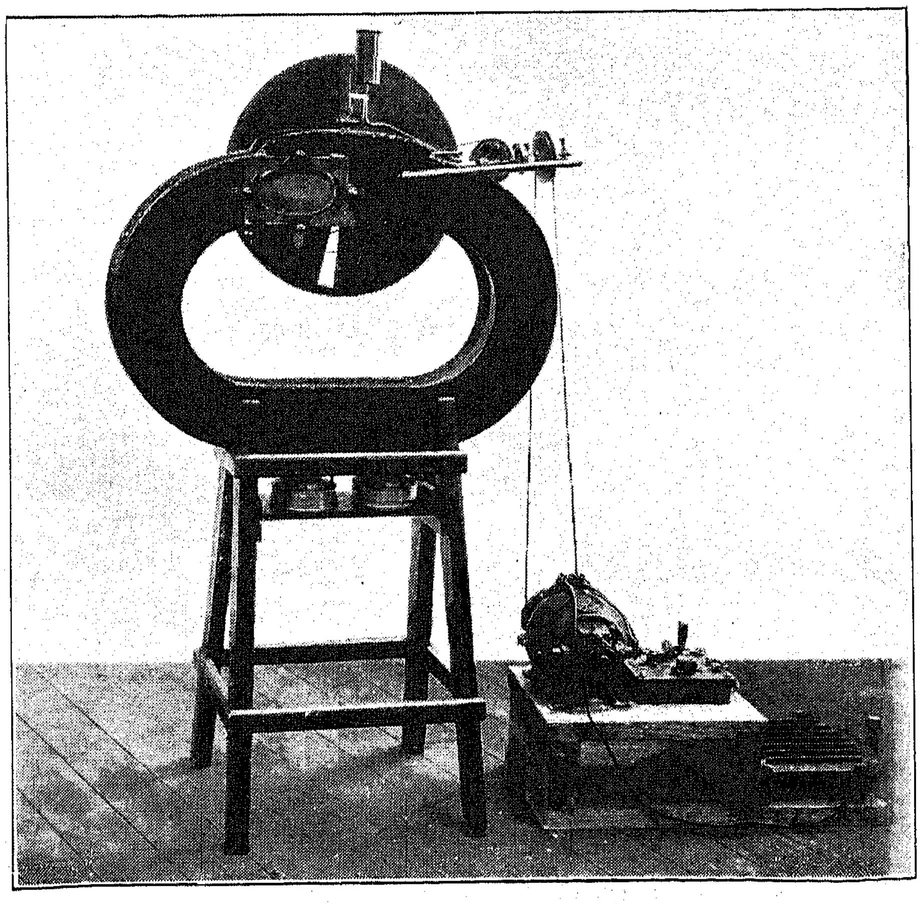

Fig. 9.—Cavitation tank.

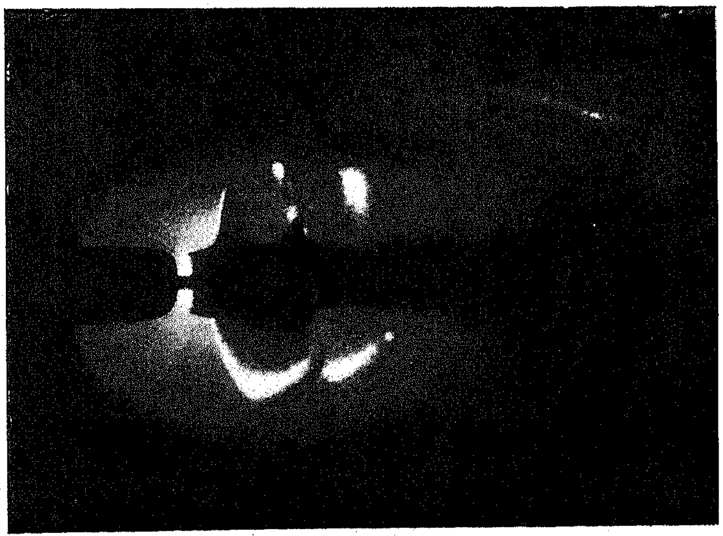

Fig. 10.—Cavitation photograph.

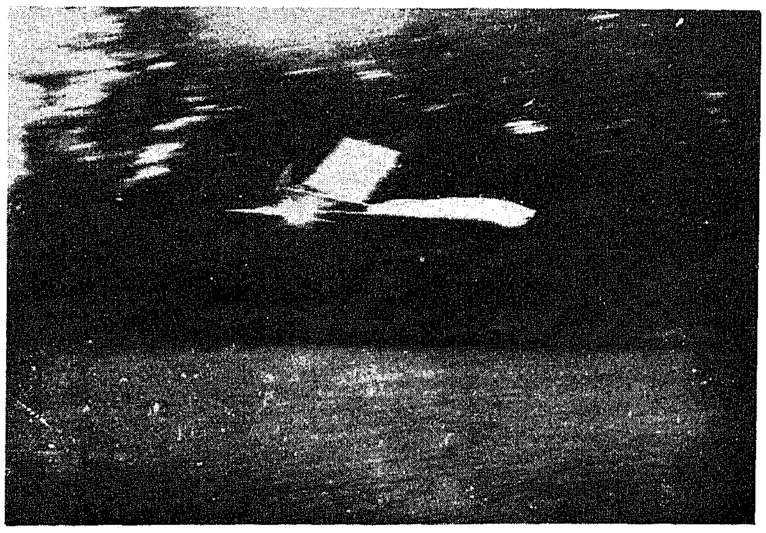

Fig. 17.—Model aeroplane in flight.

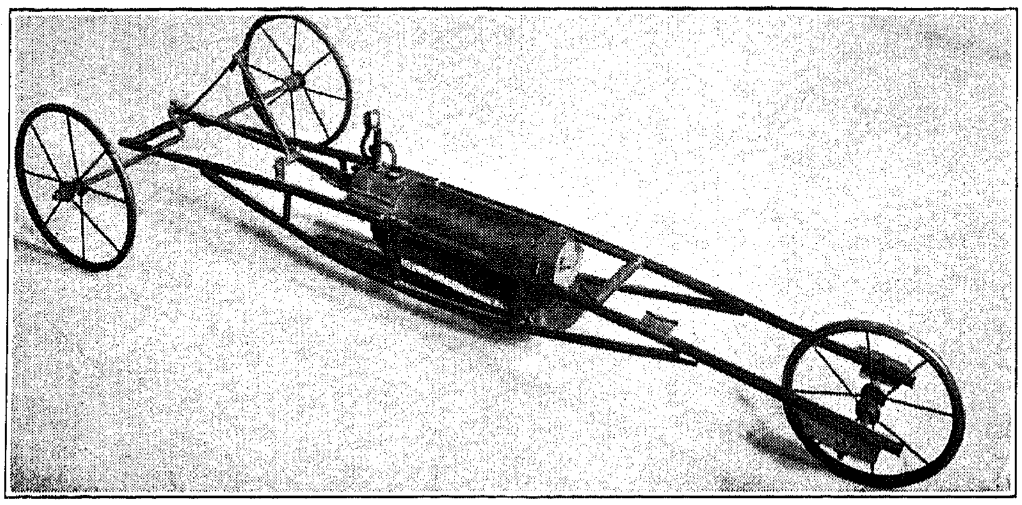

Fig. 18.—" The Spider."

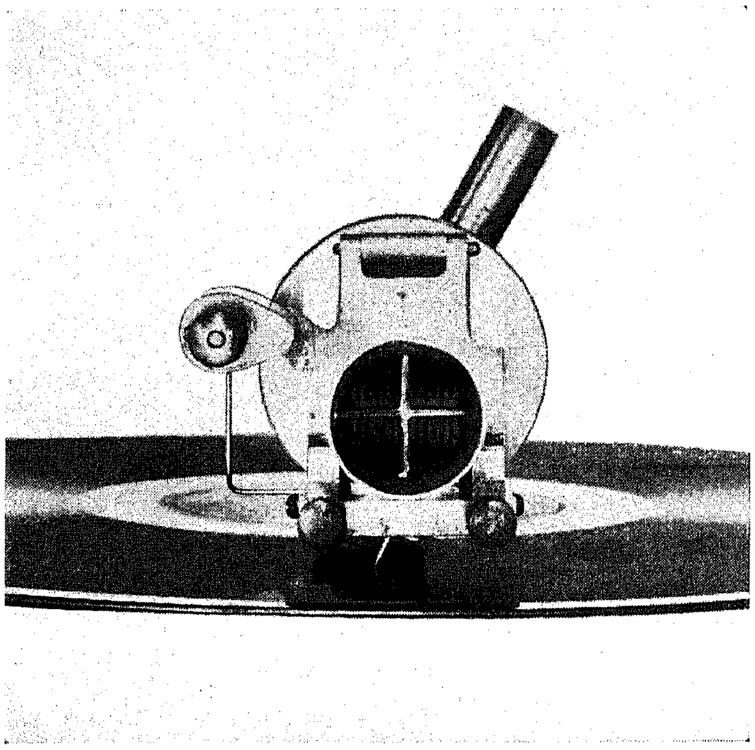

Fig. 19.—Auxetophone on gramophone record.

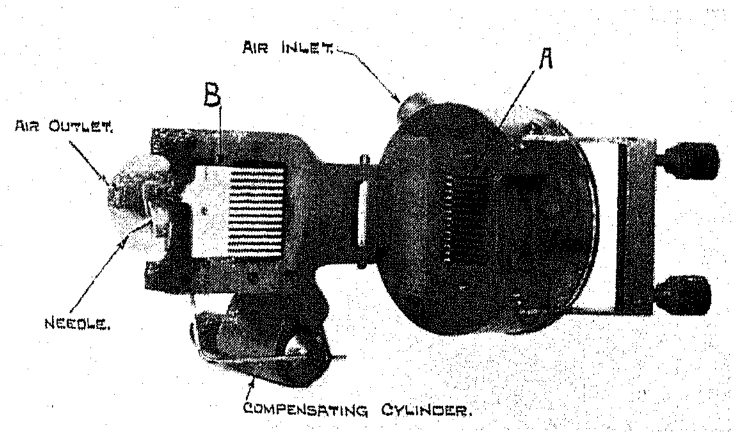

Fig. 20.—Details of Auxetophone.

powers were exceptional. He had great faith in the "rule of three," which he used in a marvellous way. He was able to arrive, apparently in some sub-conscious way, at conclusions which were almost invariably correct. He made little or no use of mechanical or graphic aids to calculation, and never gave more than a casual glance at the estimated performance of a turbine set out on a Mollier diagram. It is uncertain whether he ever appreciated the value of diagrams of this kind, while he regarded the idea of entropy as a needless mystification. Fortunately, however, he had no objection to his staff working with entropy, slide rules, Mollier diagrams, or anything else they thought fit.

Many a puzzle we used to have over bits of paper he left after a conference over a design. I well remember the day when he sprang what is now universally known as the "Parsons coefficient," K, upon us, with no more explanation than that it had the value $K = NR^2D^2 \times 10^{-9}$ where N is the number of rows on the cylinder or spindle, R is the number of revolutions per minute, and D the mean diameter of the blading in inches, a summation being made for the various stages of the turbine. At that time all we knew was that K was a figure related both to the turbine efficiency and to the ratio of blade speed to steam speed, and it took a good deal of cogitation before we discovered that this ratio, u/c, was equal to $\sqrt{[K/(1\cdot3\Delta H)]}$ for a reaction turbine, where ΔH denotes the heat drop. I have often wondered what connection there was in Parsons' mind between efficiency, velocity ratio, and heat drop. He never told us, but accepted the above formula when it was suggested to him.

Parsons had an extraordinary intuition on all matters connected with design. No matter how difficult or novel the problem, he seemed to know instinctively how to solve it. Furthermore, he was often able to proceed directly to the best solution. As an example of this I may mention the blade form of reaction turbines. In the early machines the blades were machined on the circumference of solid rings of metal, and their form was conditioned largely by the limitations due to the methods of manufacture. Various alterations were made as time went on, but the necessities of manufacture remained a controlling influence in regard to the shape. When drawn strip became available, Parsons in 1896 devised the present principle of blading, in which drawn blades of accurate section alternate with suitably-shaped spacing-pieces. The blade-shape and the spacing illustrated in his patent of 1896 proved practically perfect for turbines with the moderate velocity-ratios of 0·5 to 0·65 employed in those days and for many years afterwards. Except for slight improvements in detail, such as sharper edges and better finish, both blades and spacing have remained virtually unchanged to the present day, in spite of numerous investigations and experiments carried out with the object of finding a superior shape. For higher velocity-ratios slight modifications have been found advisable, but for the conditions for which the blades were designed it may be said that the form and spacing were ideal. The prescience of Parsons seems all the more remarkable when it is remembered that in 1896 the present knowledge of aerofoil shapes and of aerodynamics was non-existent.

Not only was he endowed with a thoroughly practical type of mind, but he had also great mechanical aptitude. He was perfectly familiar with all workshop processes, and had unusual skill with his hands. He took a delight in making models, not as ends in themselves, but as means of studying some problem in which he was interested. These models were rarely very elaborate, but so well were they adapted to the purpose in view and so great was Parsons' ability as an experimenter, that he was able to obtain very accurate results from quite crude apparatus. Before building the famous "Turbinia" he decided on the form of the hull by towing variously-shaped small models by means of a fishing rod and line in a pond in his garden. He then made a larger model, about 6 ft. long, and towed it across the cooling pond at the Heaton Works by the power of a falling weight. From these and other simple experiments he deduced the power that would be required for the actual vessel at full speed, and it is a remarkable fact that when this was determined some years later, by model experiments in the Government tank carried out with all the scientific resources at the disposal of the authorities, the results agreed with those obtained by Parsons within 2–3 %.

THE FIRST TURBO-GENERATOR

It was in 1884 that Parsons constructed the first steam turbine. This was a parallel-flow machine developing about 10 h.p. at 18 000 r.p.m. The speed at which it ran gave rise to many new problems, such as, for example, the design of suitable bearings and the provision for their lubrication, but an even more difficult question was that of utilizing the power of a turbine running at such a speed. The only practical course was to employ the turbine to drive a dynamo, but the dynamo itself had to be specially designed because the dynamos of those days were chiefly belt or rope-driven machines running at about 1 200 r.p.m. It was an enormous step to go from 1 200 r.p.m. to 18 000 r.p.m., especially as both mechanical and electrical science was then rudimentary in comparison with modern knowledge, and the materials available were also much inferior. It should be remembered that, in 1884, the theory of the magnetic circuit had not yet been propounded; it was not till 1886 that the late Professors John and Edward Hopkinson established the principles of the magnetic circuit on a firm basis. Their historic paper appeared in the *Philosophical Transactions* of the Royal Society of that year, and by a coincidence Osborne Reynolds's equally famous paper on film lubrication of bearings was published in the same volume. Just as the Hopkinsons prepared the way for the scientific design of electrical machines so did Reynolds lay down the principles of lubrication and prepare the way for Michell, without whose design of pivoted pad thrust-bearings the modern geared marine turbine would be practically impossible, and the construction of large land turbines would be severely handicapped.

As an example of how little was known concerning electrical design at this time, I may mention an incident which occurred about 1881, when I was a boy of about 18 years of age. I was present at a discussion at Sir Howard Grubb's Optical Works in Dublin, between Sir Howard, William Wilson, and my father, G. Johnstone Stoney, all Fellows of the Royal Society. The question under discussion was why a Siemens dynamo, which was used for supplying current for some arc lamps at the works, ran so hot. The dynamo had a solid shuttle-wound armature, and apparently absorbed about as much power at no load as when the arc lamps were working. All were agreed that the I^2R losses were insufficient to account for the heating, but no satisfactory explanation of it could be devised, and it was finally decided that the best thing to do was to drill a hole through the armature and pass cooling water through it. This was, in fact, done. Nobody knew anything about hysteresis effects or eddy currents in those days, although knowledge quickly increased and by 1884 laminated armatures were already in use.

In getting out the design for his first turbo-dynamo, Parsons has told me that he took as his basis a 1 200-r.p.m. machine, made, I believe, by Siemens. From this, guided partly by intuition and partly by some sort of "rule of three" of which he knew how to make the most extraordinary applications, he proceeded to the design of a dynamo to generate 4·5 kW at 65 volts at a speed of 18 000 r.p.m. The armature of this machine is illustrated in Fig. 2. Its length between bearing centres was about 27·5 in., the bearings being of 0·5 in. diameter and 3·5 in. long. The shaft was of high-carbon steel, 1·25 in. diameter, and was bored through from end to end, partly as a means of conveying oil to the bearings and partly so that the oil might serve as a cooling medium for the armature. This method of cooling was soon abandoned, as it was not very efficient, and it had the further disadvantage of heating the oil. It may be mentioned that the circulation of water instead of oil through the rotors of large alternators for cooling purposes was resorted to about 1914, but the principle was again abandoned.

The core of the armature was of 2·25 in. diameter by 8 in. long, and was built up of thin iron laminations threaded on the shaft. It had a drum winding with 50 conductors on its surface. Fibre discs with notches around their circumference were fixed at each end of the core to give a positive drive to the winding. The latter was held in place by a layer of binding wire, which brought up the final diameter of the armature to about 2·625 in. At first the binding wire was of phosphor bronze, but this proved unsuitable owing to its liability to soft spots, which resulted in breakages. Steel piano-wire was adopted later, and gave satisfaction in spite of its magnetic properties. The commutator was composed of 25 segments. The individual bars were not continuous, but each was formed of 6 separate lengths, engaging with intermediate dovetailed holding rings, the whole being held together by the end-pressure of the tightening nut. The bars were insulated from each other and from the shaft and holding rings by sheet asbestos. In such an armature, every pound mass at the surface has associated with it a centrifugal force of about 5 tons at the normal speed of the machine, so that great care had to be taken to make the construction sufficiently strong to resist the mechanical stresses. Regarding the armature from the electrical point of view, supposing 90 % of the core to be iron, the magnetic density was about 9 500 lines per cm², and there were about 375 ampere-turns per inch diameter of core. Constants such as these were adhered to for surface-wound armatures for many years, the magnetic density being kept between 8 000 and 10 000 lines per cm², although in larger machines with greatly increased air-gaps as many as 1 300 ampere-turns per inch diameter were sometimes allowed.

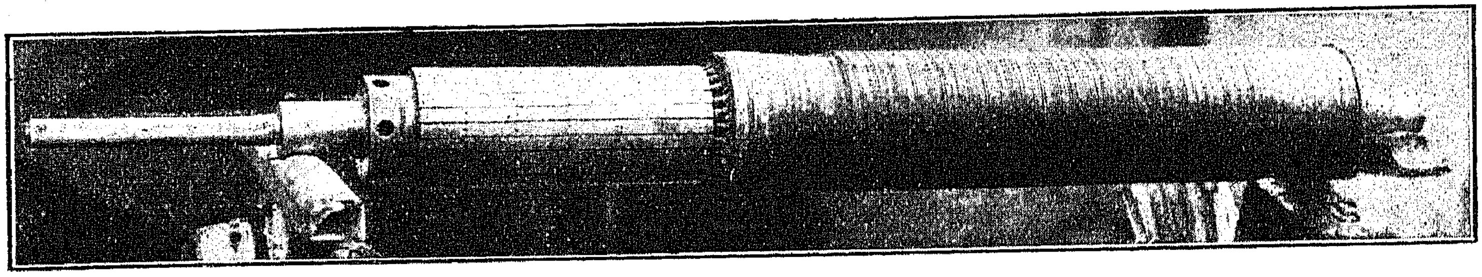

Fig. 2.—Armature of early turbo-dynamo.

Between 1889 and 1894 Parsons temporarily lost control over his original patents, and this compelled him to resort to other methods of dynamo construction. During this period, therefore, he built machines with Gramme armatures. Although these had twice as many commutator segments as machines with drum armatures, they were more subject to sparking at the brushes, while heating troubles occurred owing to the congestion of the windings inside the core, and the rotation of the shaft in the stationary magnetic field. An attempt was made to reduce the heating from the latter cause, by winding insulated iron wire on the shaft, but this further reduced the ventilation of the congested interior of the core. The largest Gramme ring machines made by Parsons developed 410 kW at 120 volts and 3 000 r.p.m., this output being obtained by the use of two armatures mounted in tandem on the same shaft. On the recovery of the patents, the drum type of armature was immediately reverted to, and was used with few exceptions until—to everybody's relief—the introduction of gearing enabled the high-speed dynamo to be given up.

About the largest turbo-dynamo with a drum-wound armature was a machine developing 900 kW at 500 volts and 1 080 r.p.m. The brushes on these early machines were either of brass wire, or of brass or copper gauze wound into the form of broad rectangular bars. Carbon brushes were not used for high-speed commutators until about 20 years later, when they became possible owing to improvements in carbons and brush-holders, and to better balance of the armatures. The construction of commutators with short segments connected by dovetailed rings was superseded about 1890 by the method of using steel rings shrunk on over mica insulation, to hold the bars in position. It is curious that this great improvement, which constitutes probably the best way of making a high-speed commutator, was never patented, for Parsons, as a rule, took care to patent all his inventions.

The bearings of all the early turbines and dynamos were made flexible to enable the shafts to run without vibration, as before the working speed was attained two or even three critical speeds had sometimes to be passed through. The first type of bearing consisted of a bronze bush surrounded by a series of washers alternately fitting the bush and the pedestal. The bush was prevented from turning by a pin, and the washers were kept tightly in contact with each other by the pressure of a helical spring. The arrangement permitted the shaft both to align itself and to rotate about its centre of gravity, while the friction between the washers provided the necessary damping effect. The bearings worked perfectly, but in time the edges of the washers wore into the bush and the pedestal. In 1889 the design was modified by replacing the washers by three concentric tubes fitting loosely over the bush, the film of oil between the tubes giving the necessary damping effect. An ample oil supply was provided by a pump driven from the turbine spindle. These bearings continued in use for many years, until the increased size of machines and the better balance of the rotating parts rendered them unnecessary. Few better examples of Parsons' intuition can be given than the fact that the proportions of his first turbo-dynamo, designed 53 years ago when electrical knowledge was so rudimentary, could, so far as I know, hardly be improved upon to-day, and certainly could not have been for more than a quarter of a century after the machine was constructed.

The early turbo-dynamos were practically always simple shunt-wound machines, whose voltage was kept constant by an electrical governor which varied the speed as required. One of the troubles associated with these machines was the violent sparking which occurred at the commutator unless the brushes were shifted to suit the changes in load. To relieve the attendant of this duty an arrangement was devised to shift the brushes automatically. This was done by means of a steam cylinder having a spring-loaded piston which was acted upon by the steam pressure at the entrance to the first row of blading. Since this pressure is proportional to the load on the turbine, the position of the piston is proportional to the load, and by connecting the piston to the brush-gear the brushes were rocked backwards or forwards as required. The defect of the device was the time-lag in its action, which permitted a momentary violent sparking at the brushes when a large change of load occurred.

The next plan was to use a compensating winding to neutralize the armature reaction, and thus to render the shifting of the brushes unnecessary. The winding was connected in series with the armature, and was carried in slots cut in the pole-faces. It extended sometimes round the whole circumference of the armature. The scheme worked perfectly well from an electrical point of view, but the leakage flux was so great that the ampere-turns of the compensating winding had to be two or three times as many as those of the armature; hence the quantity of copper was excessive, and there was also trouble with heating. Why interpoles, which were then coming into use, were never tried I do not know.

UNIPOLAR DYNAMOS

The unipolar dynamo, as invented by Faraday in 1831, consisted of a plain copper disc rotating between the poles of a magnet, current being collected by means of two brushes, one rubbing on the rim of the disc and the other on the shaft. Parsons built a number of dynamos embodying the same principle, which, however, was applied in a somewhat different manner. In his machines the rotor consisted of a soft iron shaft which passed through holes in the poles of a magnet. Certain portions of the shaft were covered with copper sleeves, from which the current was collected by brushes. Some of these dynamos had two magnetic poles only, in which case the current was taken from between the poles and from the ends of the rotor. In another design the magnet had a central pole of one polarity and two side poles of the opposite polarity, current then being taken from the parts of the rotor between the poles. The latter arrangement had the advantage of giving double the voltage of the other, but even so the maximum voltage was very low. The current, on the other hand, could be very large, so that the machines were suitable for electrolytic work, while their mechanical simplicity and the absence of any commutator were attractive features.

The first unipolar dynamo constructed by Parsons was made about 1887, but no records of the design exist. In 1889 he built another, which proved itself capable of welding an iron bar $\frac{3}{4}$ in. in diameter. So far as I can recollect this machine had a rotor of about 3 in. diameter, which ran at 12 000 to 18 000 r.p.m. Some years afterwards a unipolar dynamo generating 6 000 amperes at 1·25 volts when driven at 1 500 r.p.m. was built at Heaton, and there was a further machine giving 10 000 amperes, 5 volts, at 4 000 r.p.m., but the type fell into disuse owing to its limitations in respect of voltage and to the difficulties of collecting large currents from the surface of the high-speed rotor.

EARLY TURBO-ALTERNATORS

The first turbo-alternators to be built were four 75-kW 4 800-r.p.m. machines, generating single-phase current at 1 000 volts, 80 cycles per sec. These were installed in the Forth Banks power station at Newcastle-on-Tyne in 1888 and 1889. The turbines were not only the largest in existence at that time but also the first to be installed in any public power station. The next notable turbo-alternator was a 100-kW unit constructed in 1891 for the same voltage and frequency as the Forth Banks machines. The turbine was the first condensing turbine made. The set was tested by the late Sir Alfred Ewing, F.R.S., and was found to have a steam consumption of 27 lb. per kWh when supplied with steam at 100 lb. per sq. in. gauge pressure, superheated to 465° F., and exhausting into a vacuum of 28·75 in. This result was considered so satisfactory that steam turbines were selected instead of reciprocating engines for the new power stations at Cambridge and Scarborough. This turbine was kept for some time as an experimental machine, and amongst other services it rendered was the driving of a Gwynne centrifugal pump used for testing various high-speed impellers. The normal speed of the pump was 1 200 r.p.m., and it was run up to nearly 4 800 r.p.m. What water pressure was finally reached is not exactly known, for, in spite of having been strengthened for the test, the pump burst and everybody near was drenched. The unit later formed the first condensing set in the Forth Banks power station, and it now occupies a place of honour at the Heaton Works.

The Cambridge and Scarborough turbo-alternators were similar to the machine just mentioned, except that they were built to generate 150 kW at 2 000 volts. The alternators had revolving armatures with cores of 8⅞ in. diameter by 30 in. long. A 4-in. shaft, partly squared so as to allow ventilating air to pass along it, carried the core, and the air flowed through holes in the blank space between the shuttle windings. The winding comprised 192 conductors in two layers. The conductors were of 7/19 B.W.G., each strand being single cotton-covered and the whole conductor double cotton-covered and braided. Allowing for the distance-pieces on the core, the magnetic flux density was about 8 000 lines per cm^2, and the current density in the windings was 7 500 amperes per sq. in. As might have been expected, the windings got pretty hot and there was considerable trouble with the insulation both of the core and under the binding wire. The insulation consisted of cotton tape soaked in shellac varnish, this being the only available varnish at the time. A considerable improvement was found when pure silk tape was used instead of cotton.

All the early turbo-alternators were single-phase machines with rotating armatures. The armature cores carried a drum winding held in place by binding wire. The latter was steel piano-wire of 17 B.W.G., and the calculated stress allowed was 15 tons per sq. in., or about 88 lb. per wire. As the material had a tensile stress of about 120 tons per sq. in., the factor of safety was about 8. The binding wire could not be wound more closely than 12 turns per inch, in order to avoid contact, and if more turns were required two layers were put on, but this was only done in case of necessity. At the ends of the armature, outside the magnetic field, the wire could be close-wound. After each armature had been wound, temporary binding wire was put on. The armature was then dried and the final binding wire was wound on, always in one continuous length from end to end.

The breaking of the binding wire in service was not unknown, and generally happened as the result of a bad short-circuit in the armature. Guards were always fitted over the ends of the armature outside the poles, and fortunately no one was ever injured by the flying wire. In one case, possibly on account of an external short-circuit, the armature of one of the 150-kW alternators burst. The squared end of the shaft sheared off where it entered the coupling, and as the governor valve had been allowed to become leaky, and no runaway valves were then fitted, the turbine ran away. Before steam could be shut off at the boilers the turbine was wrecked. It was one of the radial-flow machines, built about 1892, and some of the high-pressure discs, which were of cast-iron, burst. The low-pressure disc, made from mild-steel boiler-plate, did not burst but stretched and of course sheared off all the blading. This disc was of 27 in. diameter and ran normally at 4 800 r.p.m., having thus a peripheral speed of about 560 ft. per sec. It carried six rows of blades on each side, and had a ring of holes near the centre to allow steam to pass through to the blading on the back. Neglecting the loading due to the blades, and the effect of the holes, the stress at the bore of the disc was about 12 tons per sq. in., so that the real stress at that point must have been close to the elastic limit of the material, of which the ultimate strength was between 27 and 30 tons per sq. in. It must be remembered that 45 years ago very little was known about the stresses in rotating discs.

As a result of the runaway, the disc stretched sufficiently to increase its diameter from 27 in. to 27¼ in. It was considered curious that the diameter of the bore, which was originally 4 in., increased by the same amount, being found to measure 4¼ in. after the accident, although modern theory shows that such a result is to be expected. Discs of the type in question sometimes became loose in service, probably on account of having been run up to overspeed and thereby stretched. When this happened they were bored out and bushed, after which they rarely became loose again.

A later development in the construction of rotating armatures for alternators was to wind the conductors through tunnels in the core, and to retain them by end-caps of manganese bronze. This was the practice adopted in the 1 000-kW turbo-alternators built for the City of Elberfeld in 1900, which were the largest machines of that kind. They ran at 1 500 r.p.m. and generated single-phase current at 4 000 volts, 50 cycles per sec. The Elberfeld turbines were the first ones for land service to be built with separate high- and low-pressure cylinders in tandem, although the designs for a tandem turbine had been prepared as early as 1889. It may also be mentioned that in 1896 a turbine having separate high-pressure, intermediate, and low-pressure cylinders, each driving its own propeller shaft, was used on the famous "Turbinia," the first vessel to be driven by turbine machinery.

Although rotating armatures gave reasonable satisfaction for single-phase turbo-alternators, they proved almost hopeless when 3-phase machines of high voltage came to be constructed, and were abandoned in consequence of the troubles experienced with a 1 500-kW 3-phase alternator generating at 6 000 volts, 40 cycles per sec., and running at 1 200 r.p.m., installed in the Neptune Bank station of the Newcastle-on-Tyne Electric Supply Co. in 1902. The insulation between the four slip-rings from which the current was collected was continually breaking down, but an even more serious difficulty was the crushing by centrifugal force and consequent failure of the insulation where the conductors crossed each other under the end-caps. Single-phase alternators did not suffer in this way, as in such machines there was no crossing of the conductors. To get over the difficulties of the revolving armature the present type of turbo-alternator was adopted, with a stationary armature and rotating field magnets. At first the rotor had salient poles, but soon the now universal barrel type of rotor was adopted.

Some of the practice of these early days now seems very primitive, but one must remember that Parsons was breaking new ground in almost every direction, with little or nothing to guide him but his own intuition. Books such as we have in abundance nowadays on steam, electricity, and in fact every branch of engineering, were either non-existent or extremely elementary. There were no steam tables, and no data except Regnault's experiments on saturated steam, and the science of thermodynamics had hardly been born. Similar conditions existed as regards electrical knowledge. Measuring instruments, as we know them to-day, did not exist, and the range and quality of materials for constructional or insulating purposes was very restricted.

Many of the principles advocated by Parsons years ago are now universally accepted. He maintained, for instance, that the high-pressure end of a steam turbine should be of small diameter to permit of a fair blade-height, while the low pressure end should be of larger diameter to allow for the increased volume of the steam. It was long before the soundness of this was realized by makers of impulse turbines. Owing to the possibility of securing a reasonable blade height by means of partial admission in such machines, it was formerly common to make all the wheels of the same, or approximately the same mean diameter, with the result of excessive losses due to the partial admission and to undue disc friction at the high-pressure end. Parsons also introduced the practice of carrying out the expansion of the steam in two or more cylinders, when the size of the machine or the range of temperature made this desirable. The employment of double-flow low-pressure cylinders, in order to deal with large volumes of steam at very low pressures without recourse to unduly long blades, was another of his inventions. So long ago as 1889 he designed the tandem condensing turbine, illustrated in Fig. 3. In this machine the high-pressure cylinder was to be one of the standard non-condensing turbines of that date, while the low-pressure cylinder was a double-ended one of larger diameter. This machine was never actually built, however, because of partnership troubles supervening, and the first tandem turbine for land work was not constructed till 10 years later. In Fig. 4 there is reproduced a drawing of the low-pressure cylinder of the turbine shown in Fig. 3, and I may say that the design of this cylinder was one of the first jobs I had after I joined Parsons in 1888. It will be noticed that the condenser was placed under the generator, and formed a support for the latter, a design often adopted now for small industrial machines.

In the days of which I am speaking, the blades were generally cut on the edge of rings which were threaded on the shaft. The blades had no shrouding, and their tips ran nearly in contact with the cylinder. In this particular turbine, however, the blades were shrouded as shown in Fig. 4. The shroud was made with two or three projecting knife-edges around its circumference. A modified form of this shrouding was used for many years by Messrs. Willans and Robinson, Ltd., of Rugby, who were licensees of Parsons. Here we have an early illustration of the principle, always upheld by him, that when there is a small clearance and a high relative speed between two adjacent parts, one or other must be so thin that its edge may wear away without serious trouble from heating or expansion in the event of contact occurring. If two broad surfaces touch under the conditions stated, heating takes place, with consequent expansion and distortion; the friction then becomes greater and may end in a smash-up. It was some time before the necessity of really thin knife-edges was realized by turbine engineers, but the fact is now unquestioned. In accordance with this principle, Parsons introduced thin tipped blades in 1905. The step was a great improvement, as it allowed turbines to be run with fine clearances without fear of the blades stripping in cases of accidental contact, and so eliminated one of the great drawbacks of the early turbines.

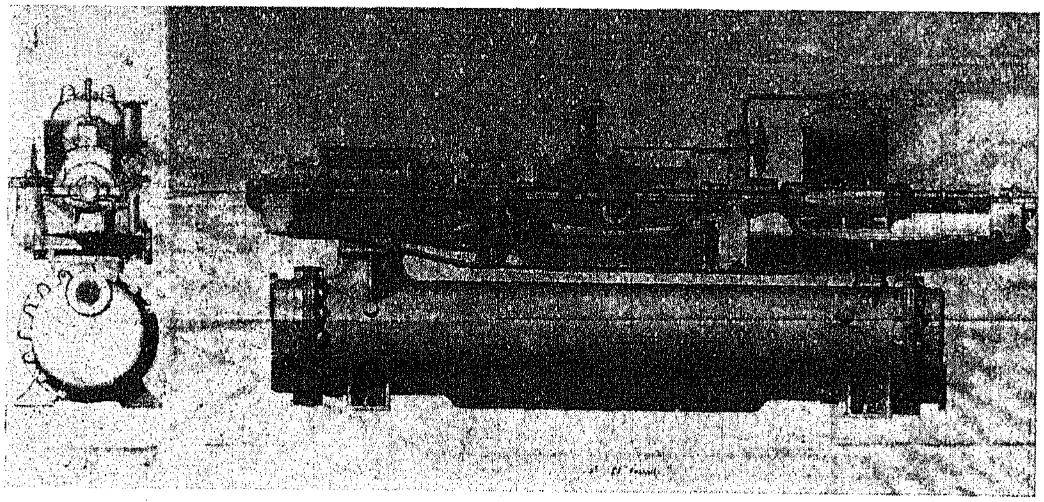

Fig. 3.—Design for early tandem turbo-dynamo.

Returning to the subject of turbo-alternators, it was not until after 1908 that high-speed machines of large output began to be made. In that year a 5 000-kW turbo-alternator running at 2 400 r.p.m. was representative of the most advanced practice. In 1912 a 25 000-kW machine at 750 r.p.m. was built for Chicago, and it is worthy of note that it is still in service at the present day. A year or two afterwards an output of 11 000 kW at 2 400 r.p.m. was reached. It must be remembered that, for machines of similar design, whether turbines or alternators, the output varies almost inversely as the square of the number of revolutions per minute. Hence a unit rated at 11 000 kW at 2 400 r.p.m. would be comparable with another developing about 7 000 kW at 3 000 r.p.m. Machines developing 40 000 or 50 000 kW at 3 000 r.p.m. are in service at the present time, and over 100 000 kW can be developed at 1 500 r.p.m. by a single unit.

This enormous increase in size and speed has given rise to many difficult constructional problems such as the production of sound forgings of large dimensions, a matter to which Parsons gave much attention. The question was brought into prominence by the disastrous failure of a large forging employed for a turbine rotor. The rotor had passed all the usual tests, including the overspeed test, but it failed owing to a hidden flaw, caused undoubtedly by incorrect forging and heat treatment. Subsequent examination showed it to be full of internal flaws and in such a state of strain that, when it was cut up for examination, cracks developed spontaneously. Parsons took up the matter with his usual energy, and insisted that large forgings should never be allowed to cool below a good red heat from the time of pouring of the ingot until all forging operations were complete. Any reheating necessary during the process had to be carried out in accordance with strict rules. Forgemasters raised many objections at first, but were finally convinced that the system was the right one.

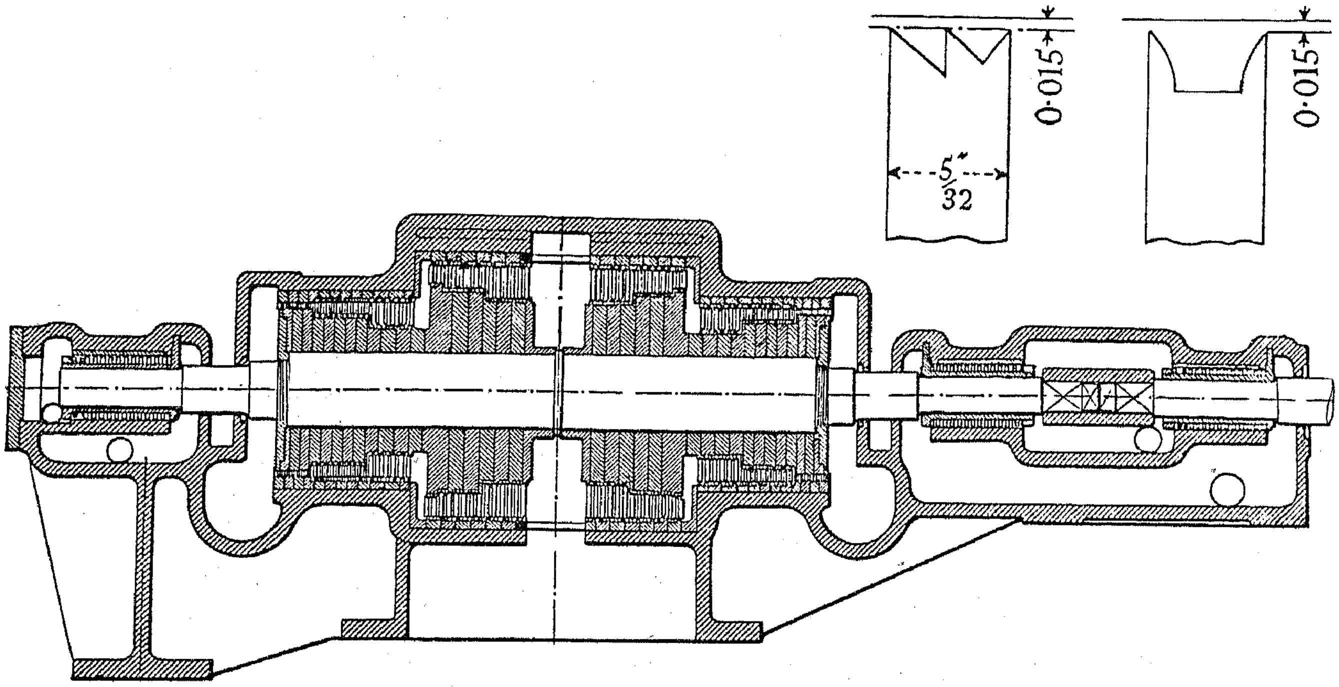

Fig. 4.—Drawing of low-pressure cylinder of turbine shown in Fig. 3.

Another improvement in steel making, due to Parsons, is a method of casting steel ingots which ensures uniform crystallization of the metal and avoids the waste due to segregation and " piping." According to this method, the molten steel is poured into a circular mould, of which the diameter is greater than the depth. The sides of the mould are of refractory material and the bottom consists of a large chill. The walls are preheated to nearly the temperature of the molten metal, and after the ingot has been poured its cooling is controlled by oil-burners playing upon it from the cover of the mould. This ensures that the surface is the last part of the ingot to freeze. An ingot cast in this way, when cut in two, is found to be free from segregation and lines of weakness. The process was analogous to the method whereby Parsons' father, the Earl of Rosse, succeeded in casting the great mirror of speculum metal, 6 ft. in diameter, for the famous telescope at Birr, in 1845. The metal was poured on to a bed of hoop-iron, figured to the curve of the mirror. The porosity of the bed allowed the gases to escape and the crystallization to be regular as the casting cooled.

CONDENSING PLANT

Parsons recognized very early that the economy of a steam turbine would be greatly improved by the use of a condenser. He realized that the turbine could make full use of the highest vacuum obtainable, and thus develop all the power represented by the " toe " of the indicator diagram, which was unavailable for the ordinary reciprocating engine. It was also evident to him that the low-pressure end of a condensing turbine would be very efficient, because the great specific volume of the steam when below atmospheric pressure would make the loss by leakage of much less importance than at the high-pressure end. He was therefore very keen on improving the vacuum in condensers. One device he adopted was the use of compound air-pumps, which he employed largely for condensers both of the jet and of the surface type. The jet condensers were provided with separate air and water pumps, a small quantity of water being admitted into the air pump to keep it cool. All the early surface condensers had wet pumps only, which removed both air and condensate together. To maintain a good vacuum with pumps of this kind, the condensate has to be as cool as possible in order to reduce the volume of the accompanying air and vapour. In some cases, therefore, it was the practice to have a weir in the bottom of the condenser, so that the condensate was maintained above the level of the lower tubes, and was thus cooled by the circulating water. The loss of efficiency due to the cold condensate was not considered in those days, the only object being to get as low a steam consumption as possible for the turbine. Parsons made many improvements in condensing plant, one of the most important being the use of a steam jet for removing air. He patented this in 1903, and the method is now universally employed.

TURBO PUMPS, FANS, AND COMPRESSORS

Although the first use of the steam turbine was for the driving of electric generators, for which its high speed made it specially suitable, the driving of pumps, fans, compressors, etc., was equally in Parsons' mind, as is proved by the claims of his 1884 patents. I have already described how a centrifugal pump was coupled to the first condensing turbine for experimental purposes. As a result of the information thus gained, several turbo-pumps were made. One of the difficulties encountered in such high-speed pumps was that of getting the water to flow into the eye of the runner. It was found that this difficulty could be surmounted by the use of small impellers, with a fixed row of guide blades between them, mounted on the shaft for the purpose of giving an axial velocity to the water before it reached the runner. By means of this device suction lifts of 11 ft. or more could be dealt with. Some pumps were built which consisted only of rows of propeller blades alternating with fixed guide blades. Others were constructed with several runners in series, and these, made some 34 years ago, were the prototypes of the modern centrifugal boiler feed-pumps.

High-speed fans and air compressors fall mainly into two classes, the first including apparatus such as colliery ventilating fans for dealing with large volumes of air at pressures from 2 in. to 6 in. water gauge, and the second supplying air at pressures from 15 to 80 lb. per sq. in. for blast furnaces, pneumatic drills, etc. The speed of a turbine is too great for the direct driving of large centrifugal fans, so that, before gearing was introduced, turbine-driven fans for colliery ventilation had to be of the impeller type. The first of such fans was built in 1896 for the Clara Vale pit, some miles west of Newcastle. Its duty was to deliver 120 000 cu. ft. of air per minute under a suction head of 2·5 in. water gauge. The fan was a simple 4-blade propeller of the marine type with blades of boiler-plate riveted to a central boss of cast steel. The air was led to the fan by an inlet cone and discharged through a corresponding outlet cone. When first put into service, the fan emitted a shrill musical note which could be heard for miles. This trouble was cured to some extent by placing a grid in front of the inlet to equalize and direct the flow of the air. Afterwards a 40-blade propeller was substituted for the 4-blade one, and the efficiency was further improved by providing an annular diffuser of conical form on the delivery side. The fan ran with practically no attention. The turbine was housed in a locked shed and visited twice a day by a fireman whose duty it was to see that it had plenty of oil. Several turbine-driven fans of the same type were made, but all of them laboured under the disadvantage that the turbines could not be run at their most economical speed. The fans, moreover, were noisy and relatively inefficient, as nothing was then known of aerofoil shapes or aerodynamics. To-day it is possible to make efficient propeller fans by applying to their design the knowledge acquired in aeroplane research. The trouble with noise nevertheless continues unless the speed of the blade-tips is kept moderate. Furthermore, if air has to be delivered at more than a low water-gauge pressure, it is necessary to use several rows of impeller blades in series with suitable guide-blades between them, and the design becomes unsuitable for direct driving by a steam turbine.

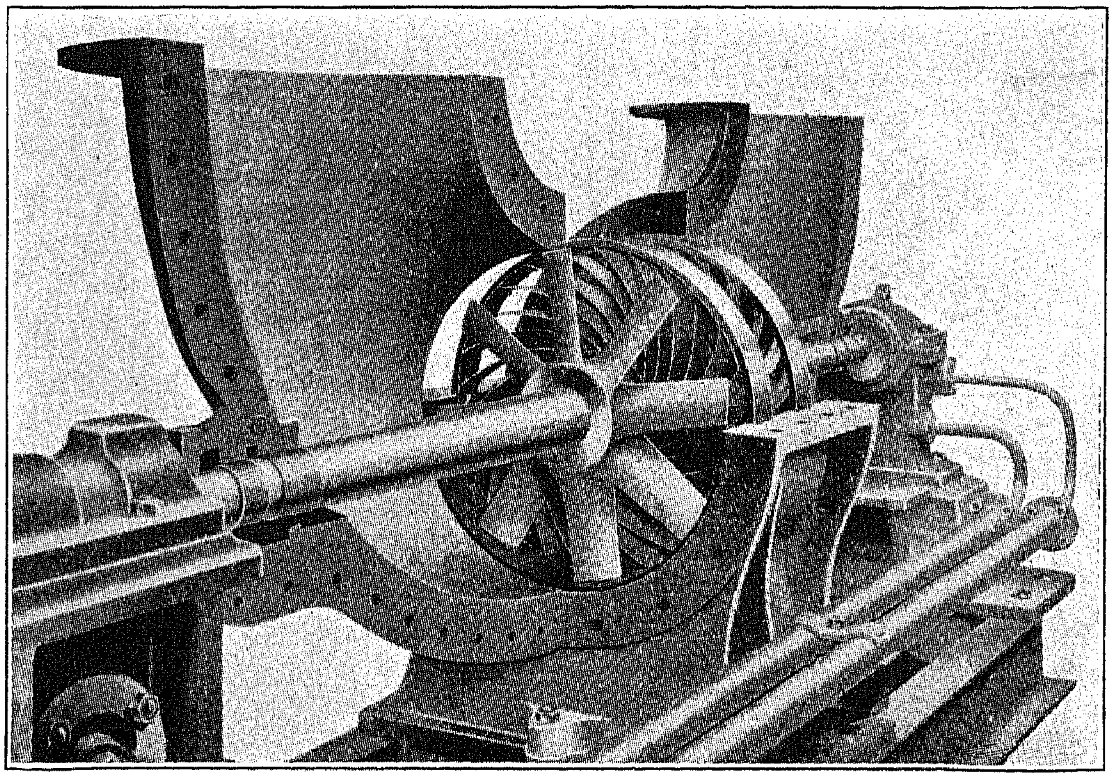

Fig. 5.—Turbo-exhauster.

Parsons also turned his attention to exhausters and blowers for dealing with blast-furnace gas, coal gas, etc. Such machines for delivering volumes of the order of 30 000 cu. ft. per min. at 30 in. water gauge had, as shown in Fig. 5, three or more fans in series, with intermediate guide blades. Being entirely enclosed, they gave no trouble from noise. They were a great improvement on the old low-speed exhausters of the revolving type driven by reciprocating engines, as such exhausters frequently become clogged up with tar, and the cost of repairs and maintenance was heavy. The turbo-blowers, moreover, saved a large amount of space.

For the higher pressures required for blast-furnace work, parallel-flow blowers were made as early as 1901. They ranged in capacity from 3 000 to 30 000 cu. ft. of air per minute and delivered at pressures from 2 to 15 lb. per sq. in. The machines had cylindrical drums carrying numerous rows of running blades which alternated with rows of fixed blades, as shown in Figs. 6 and 7. Their efficiency was not high, reaching only about 55 %. An attempt to construct a machine on these lines to compress 4 000 cu. ft. of air per minute to a pressure of 80 lb. per sq. in. led to difficulties. The design comprised two bladed drums arranged in tandem in a single cylinder, with a diaphragm between. The air was compressed to 25 lb. per sq. in. by the first drum, and then led out of the cylinder to a cooler beneath. After cooling, it was returned to the cylinder and raised to its final pressure. Each half of the machine worked very well by itself, but when the two were operated in series they proved unstable, and finally after many trials the machine was given up. This was one of the very few cases in which Parsons did not make a success of what he had set out to do.

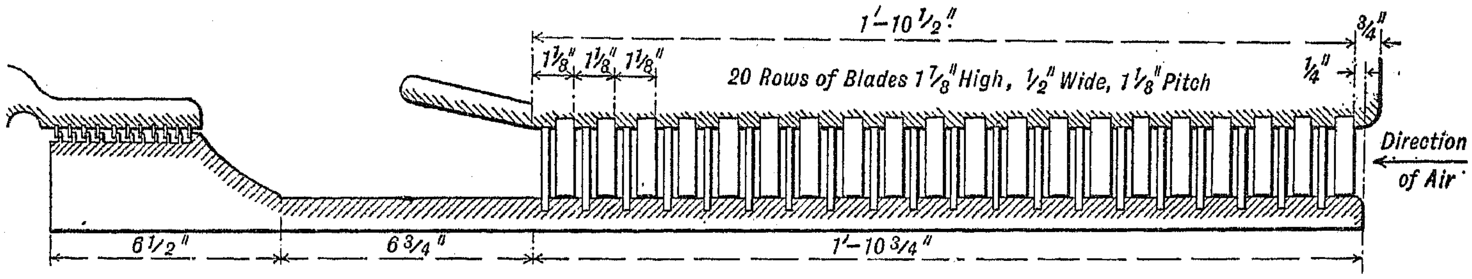

Fig. 6.—Parallel-flow compressor.

As a result of this experience he adopted the centrifugal type of compressor, which proved more efficient but was at the same time more complicated and costly. This type is now in general use. I believe, however, that by the proper application of our present knowledge of aerofoils, parallel-flow compressors, with all their advantages of simplicity and cheapness, could now be made thoroughly efficient machines. Indeed, I understand that much has already been done in this direction on the Continent, but I have been unable to hear of any corresponding progress in this country. I trust that the outcome will not be the payment of royalties abroad for designs that ought to be developed at home. The matter is worth the attention of our manufacturers, as there is reason to believe that for many purposes the parallel-flow compressor will supersede the centrifugal type.

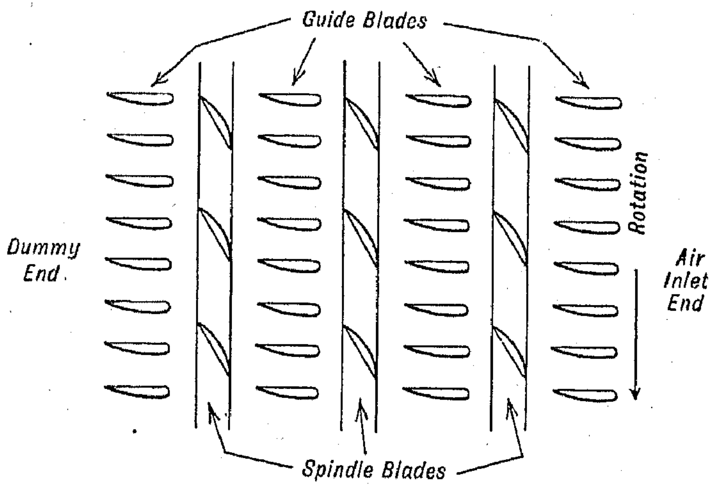

Fig. 7.—Blading of parallel-flow compressor shown in Fig. 6.

WORK ON CAVITATION

Although, as already mentioned, I do not propose to consider the application of the turbine to marine propulsion, as this has already been ably dealt with by Sir Frank Smith, and may well be discussed in greater detail in future lectures of this series, I should like to say a few words about one of the problems that arose in connection with this work, namely the question of cavitation. I feel the more justified in referring to it because cavitation troubles are not confined to ships' propellers, but also concern the designs of centrifugal pumps, water turbines, and other machinery.

When any part of a propeller blade is moving so fast that the hydraulic head is not sufficient to cause the water to follow the blade, a vacuous space is formed, which results in a large loss of propulsive power, while the metal of the blade may become seriously pitted. This phenomenon, now known as cavitation, was first brought into prominence in 1894 by the trials of H.M.S. "Daring," one of the early destroyers. This was about the time when Parsons was building the "Turbinia," and he therefore had no knowledge as to whether he might meet with the same difficulty. In the "Turbinia" as at first constructed there was a single turbine driving a propeller shaft at about 2 000 r.p.m. The vessel only attained a speed of about 20 knots, which was very low considering the results of model experiments on the hull, and the power of the turbine as deduced from its steam consumption. Many different kinds of propellers were tried, with no appreciable improvement, and Parsons confirmed the loss of power by fitting an ingenious spring torsion-meter of his own design, between the turbine and the propeller shaft. This apparatus, which was the forerunner of modern torsion-meters, is shown in Fig. 8 (see Plate 1). By this time the trouble in connection with H.M.S. "Daring" had been explained: cavitation was obviously the cause of the loss of power in both boats. Parsons met the situation with his characteristic vigour, and put in a new turbine with three cylinders, each driving a separate propeller shaft. On each shaft he placed three propellers in series, making nine in all, and as a result the speed was increased from 20 to 32·2 knots, and eventually to 34 knots, at a time when the fastest destroyers could only make about 27 knots.

Parsons decided to make a thorough investigation of the problem of cavitation. The phenomenon would clearly be favoured by reducing the difference between the absolute pressure of the water surrounding the propeller and the vapour pressure of the water. There were two ways of obtaining this result—either by raising the temperature of the water nearly to boiling point or by maintaining a vacuum above the water. Parsons tried both. An oval tank (illustrated in Fig. 9 on Plate 1) was constructed and in it was fitted a propeller of $2\frac{1}{2}$ in. diameter, which could be driven at 1 500–2 000 r.p.m.

The tank was provided with side windows for purposes of observation, and the propeller was strongly illuminated by intermittent light, so that it appeared to be stationary or only revolving very slowly. At first boiling water was used in the tank, but in consequence of the trouble arising from rust and dirt, cold water was substituted and a vacuum maintained above it in the tank by an air pump. A photograph of a propeller as it appeared during a test is reproduced in Fig. 10 (see Plate 1). A great deal of valuable information as to the best shape of propeller to adopt in order to avoid cavitation was gained from these experiments. Several large vacuum tanks are now in service, provided with all the apparatus for measuring thrust, slip, torque, efficiency, etc., and they have contributed greatly to the improvement of propellers.

THE EROSION OF PROPELLERS

In 1915, Lord Fisher's Board of Invention and Research appointed a committee to investigate the cause of the corrosion or erosion of marine propellers, which was causing the Admiralty considerable concern. So serious was the damage in certain instances that propellers had to be renewed even after a 3-hour trial. Parsons was a member of the Committee, and so far as I know it was he who suggested the real explanation of the trouble. He attributed it to the sudden closing-up of the vacuous spaces caused by cavitation on the surface of the propeller. He was, of course, familiar with the nature of these spaces from his earlier experiments on cavitation, and it is probable that this caused him to consider the effect of vacuous cavities closing under the pressure of the surrounding water. Calculations were made to determine what would happen under such conditions. It was shown that the pressure produced when a spherical cavity with an internal vacuum collapsed, would depend upon the ratio of the diameter of the cavity to that of the size to which it collapsed. If the ratio of cavity to final size was 20 : 1, the pressure produced would be 68 tons per sq. in., while with a ratio of 100 : 1 the pressure would be 765 tons per sq. in. Since the pressure produced by the collapse was independent of the absolute size of the cavity, it was evident that quite small cavities might cause pressures far above the elastic limit of the metal of which the propellers were composed. These pressures would crush the metal surface, and erosion would result. A careful review of cases of propeller erosion showed that Parsons' theory almost certainly afforded the true explanation.

Rapid erosion often occurs in centrifugal and other pumps, and in water turbines, especially when impeller speeds are high. It is found to take place in just those places where vacuous spaces would be formed by cavitation, and the crackling and other noises often heard are evidence of the collapse of such spaces. Experiments on a water siren which suffered from severe erosion showed that the rate of erosion depended greatly on the softness of the material; soft brass eroded rapidly, manganese bronze more slowly, and the hardest high-speed tool steel hardly at all. That hardness is the principal factor in resistance to erosion is confirmed by experience with steam-turbine blades. At the low-pressure ends of steam turbines, where the steam is very wet and the blade-speeds are high, serious erosion of the blades may occur. It is caused by the intense pressure produced when a blade moving with high velocity in a vacuum strikes a comparatively slow-moving particle of water, especially if there is a cavity in the blade at the point of contact. Blades of brass, and even of rustless iron, are rapidly eroded by this action, but the trouble has been completely cured by fixing shields of hard tool steel to the outer edges of blades running at high velocity in wet steam at low pressure.

In order to determine experimentally the intensity of the pressures produced by the collapse of a vacuous space such as occurs in cavitation, the apparatus shown in Fig. 11 was constructed. It consisted of a hollow brass cone 18 in. long and 2½ in. in diameter at the base, with ports at D for the passage of the water. In the apex of the cone was fitted an end-piece (shown in Fig. 12) with a central hole of 0·015 in. diameter. Plates of various thicknesses could be fastened to the end-piece, to close the hole.

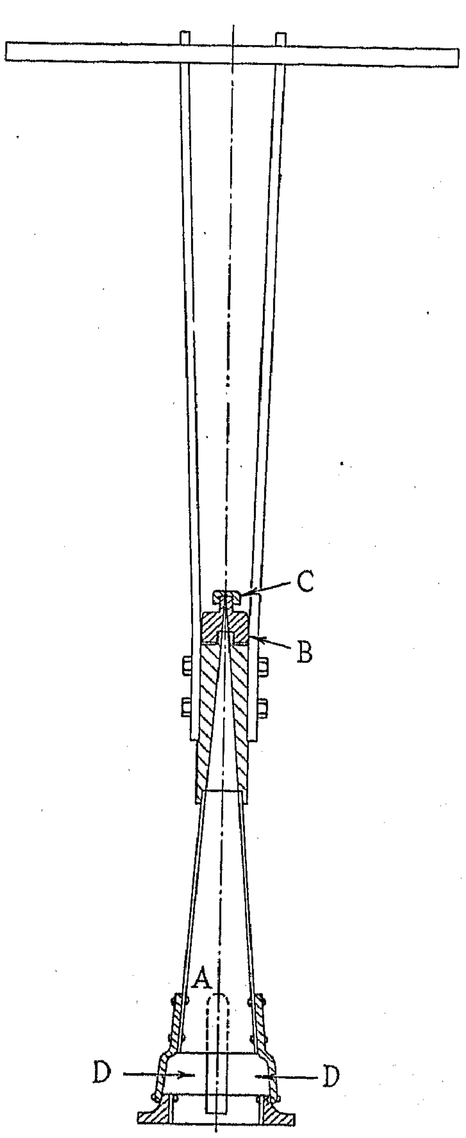

Fig. 11.—Cavitation cone.

The cone was placed in a tank of water and allowed to fill; it was then thrust downwards quickly until its motion was arrested by a rubber block at the bottom of the tank. When the cone was suddenly stopped in this way, the resilience of the rubber allowed the water to continue its motion, with the result that a vacuous space was formed at the apex of the cone. This immediately closed with a click, and the pressure produced was so great that plates of brass 0·0015 in. thick were perforated, and thicker ones were severely dented. To intensify the effect the length of the cone was increased to 4 ft. by the addition of a cylindrical portion in which a lead weight was fitted. The weight was suspended by a spring, and so placed as to cover additional ports as it descended. When the apparatus, in its new form, was thrust to the bottom of the tank, and its motion arrested, a loud metallic click was caused by the closing of the cavity. The hole at the apex had become enlarged to a diameter of 0·020 in. by the erosion, and under these conditions brass plates 0·024 in. thick were perforated. To do this the pressure must have been at least 75 tons per sq. in. With an end piece of oil-hardened tungsten steel having a hole of 0·015 in. diameter a brass plate 0·035 in. thick was perforated in two blows, the estimated pressure being 140 tons per sq. in. Attempts were then made to cause erosion of a disc of hardened novo steel, but 40 blows failed to produce any impression on it, and eventually the steel end-piece of the cone was fractured. These experiments made it clear that the pressure produced by the collapse of vacuous spaces was quite sufficient to account for the erosion of propellers. Parsons thought that a similar theory might account for the pitting of condenser tubes, but experiments carried out to test this idea were inconclusive.

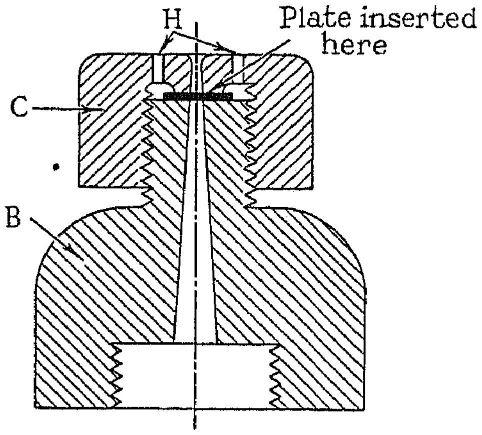

Fig. 12.—Details of cavitation cone.

WORK ON ELECTRIC LAMPS

In his younger days Parsons took up the manufacture of electric lamps, both arc and incandescent. One of his early arc lamps is illustrated in Fig. 13. The mechanism comprised a solenoid in series with the carbons, which acted on a plunger and thus drew the carbons apart, afterwards serving to maintain the current constant. The plunger was so shaped that the pull of the solenoid diminished somewhat as the carbons burnt down, thus compensating for the reduction in weight of the movable positive carbon. To keep the position of the arc constant, the lower negative carbon was adjusted upwards by hand, as it burned away. The type of arc lamp shown in Fig. 13 took currents from 60 to 150 amperes, and was designed for projector work. Smaller arc-lamps, both direct and inverted, were made for ordinary lighting purposes. Some of Parsons' arc lamps were used about 1890 to supersede "limelights" in the Empire Theatre at Newcastle, an early example of arc lighting in a theatre. A lamp of this type is shown in Fig. 14. To maintain a constant position of the arc, the negative carbon was pressed upwards by a spring against the points of the small screws, which allowed the carbon to advance as its end was burnt away.

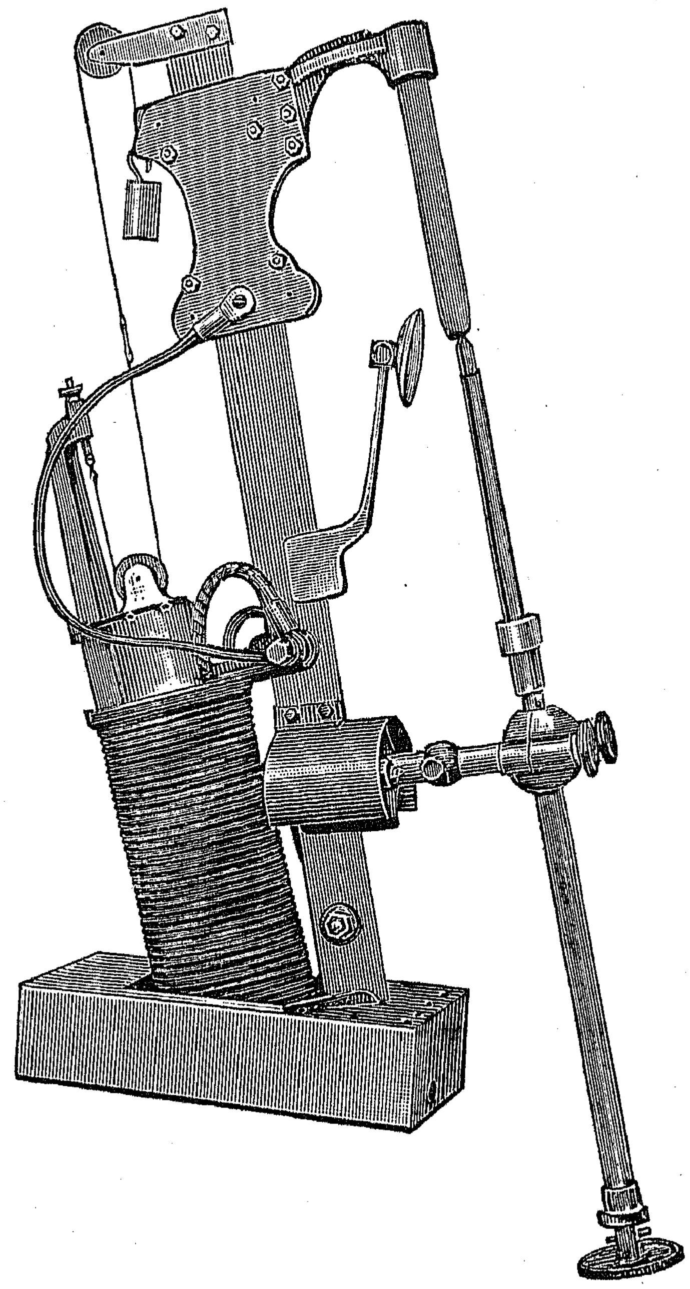

Fig. 13.—Arc lamp.

Parsons started manufacturing vacuum incandescent lamps about 1885. This was some 6 or 7 years after Swan and Edison had brought out their first carbon-filament lamps, and when the possibilities of incandescent lighting were attracting many people, in spite of difficulties due to patents. Parsons, aided by Messrs. Clarke, Chapman, Parsons and Co., of which firm he was then a partner, and by the late John W. Edmundson, founded the Sunbeam Lamp Co. Manufacture was started in the lower part of Park House, Gateshead, an old mansion since burnt down, forming at that time part of the works of Messrs. Clarke, Chapman, Parsons and Co. At first small lamps were made, but after the legal decision in a patent action that a "filament" was less than $\frac{1}{32}$ in. in diameter, the Sunbeam Lamp Co. restricted their activities to the production of lamps ranging from 100 to 3 000 candle power. Lamps of the latter size required 80 amperes at 100 volts, their consumption therefore being about 2·75 watts per candle power. In those days the usual voltage was 65, 80, or 100 volts. Lamps made by the Sunbeam Co. were employed for lighting the Newcastle Exhibition of 1887, current being supplied by 10 Parsons turbo-dynamos ranging from 16 to 32 kW, all being non-condensing. The carbons in these lamps (they must not be called "filaments," as the law had decided that a filament was a diameter of less than $\frac{1}{32}$ in.) ranged from about $\frac{1}{32}$ in. to $\frac{1}{8}$ in. or even more in diameter. They were composed of tar putty, squirted into a rod and carbonized by baking. It is difficult now, after a lapse of more than 50 years, to find out much about a process which was kept very secret at the time, but it seems that the material which was squirted consisted of tar, a special anthracite, and about 4 % of zirconia. After being baked it was connected to the leading-in-wires and heated by current in benzine vapour. This caused a deposition of carbon on the hotter, and therefore thinner, places and rendered the rod more uniform. The advantage of the zirconia was that it caused the resistance of the rod to fall with time, and the increased brilliance compensated for the blackening of the bulb.

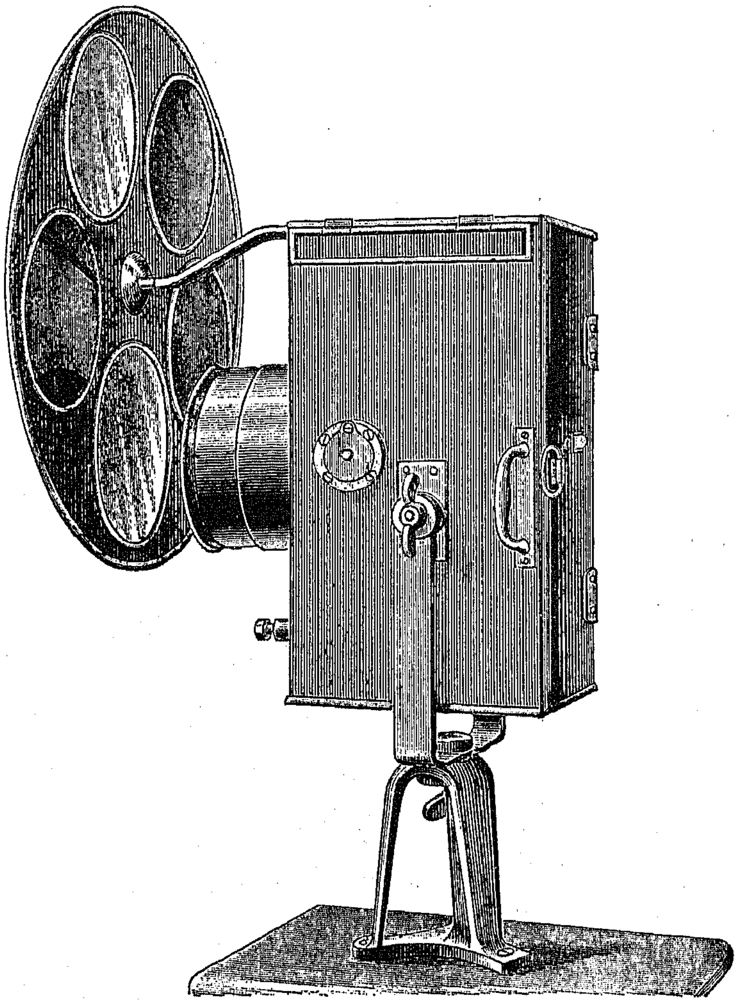

Fig. 14.—Arc lamp of the type installed at the Empire Theatre, Newcastle.

Concerning the making of these lamps, I may quote from a letter written to me by Mr. H. W. Edmundson, the son of Mr. John Edmundson, who seems to have had the run of the works as a boy. He says:—

"The carbons were made by an old man, and his apparatus was quite simple. The coal was broken up into a coarse powder in a mortar, and then ground in a coffee mill, after which it was treated with caustic soda and *aqua regia*, with prolonged washings. The resultant powder, after being dried, was ground in an agate mortar and sieved, after which it was subjected to a mysterious operation in a little cubby-hole, kept carefully locked, and called by Sir Charles the 'Holy of holies.'

"What actually took place was that the old man weighed out some of the carbon powder and some icing sugar and ground them together in a mortar with a little absolute alcohol. The function of the sugar was to act as a further binding agent when the coal powder was mixed with tar. It was kept in a bottle labelled 'arsenic.' This was done by Parsons with the idea that the old man, or anyone else, would be chary of tasting a white powder so labelled. The old man always referred to the 'white powder' and the 'black powder.' When the production of lamps went beyond the experimental stage, and the methods of manufacture had to be altered to produce larger quantities, the old man was nearly heartbroken.

"The air pump used as a backing pump to the Sprengel mercury pump was a ponderous affair with two 2-stage vertical cylinders. It continued to do good work for many years. This pump was built to Parsons' instructions."

The pump referred to by Mr. Edmundson was a compound one with a pair of cylinders 18 in. diameter by 36 in. stroke, each having a compounding cylinder of 8 in. diameter above it. The pump was single-acting and had mechanically-operated valves. These sometimes broke, as I know to my cost, having several times had the dirty and difficult job of repairing them. Nor was I the only one, for Mr. Edmundson tells of the following incident, which must have occurred before I joined Parsons at the latter end of 1888.

"I have one lively recollection of him (Parsons). He and my father had been wrestling with the pumps I have described; I expect some mercury had got into the valves, and both had their hands good and black. Parsons whipped out a beautiful clean white handkerchief and proceeded to wipe his hands on it." One of the men said: "We often saw Mr. Parsons and Tom Jefferson (a fitter) at work on the turbine which worked the generator for the lamp works, Mr. Parsons with his coat off and his nice white shirt sleeves rolled up; I often wondered what his missus would say when he got home." Parsons was never afraid of work, be it ever so dirty, as I know, from having often worked with him on a job.

Little is now known about the various ingenious devices made by Parsons for the manufacture of lamps, and after he left Gateshead in 1889 he took little further interest in the subject.

THE MANUFACTURE OF CURVED MIRRORS

Parsons always had a liking for optical work: no doubt this was an inheritance from his father, the Earl of Rosse, whose great 6-ft. telescope at Birr I have already referred to. About 1886 he became interested in searchlight reflectors, and realized that these should be figured to a parabolic form if the highest efficiency was to be attained. At that time only spherical mirrors were made in England for searchlight work, and with these the production of a parallel beam of light was theoretically impossible on account of aberration. In France, the Mangin mirror had been developed; this was in many ways an improvement, though far from perfect. The reflecting surface was still spherical, but the spherical aberration was corrected by making the glass of the mirror thicker at the circumference than at the centre. Mirrors of this type were heavy, liable to be fractured by the heat of the arc, and also expensive. About the same time the Schuckert firm in Germany succeeded in producing the desired parabolic form by grinding, but it occurred to Parsons that the cheapest and most practical method would be to bend a sheet of plate glass to parabolic form. He therefore devised a process of bending the glass when hot in an accurately figured cast-iron mould, and his original methods are used to-day with very little alteration.

When Parsons commenced making searchlight reflectors the standard sizes in use by the Admiralty were of 20 in. and 24 in. diameter, with focal lengths of 16 in. and 17⅛ in. respectively. He was able, by means of his process, to produce such mirrors of the necessary optical accuracy at less than half the cost of the Mangin and Schuckert mirrors. At first he carried on this work in a stable at Park House, Gateshead, but when he founded the Heaton Works in 1889, the equipment was transferred there. The first mirror shop was a wooden house 20 ft. × 40 ft. in dimensions, with one 4-ft. gas furnace and one polishing machine. It was soon enlarged to three times this size, and in 1905 new buildings were erected, which have since been extended several times. During the War, production greatly increased, the demand being mostly for mirrors from 12 in. to 60 in. diameter, and at the present time the output amounts to several hundred mirrors per month for searchlights and other purposes. Parabolic mirrors have been made up to 220 cm. diameter, with a focal length of 100 cm. These are probably the largest of their kind in the world, and their accuracy is such that the focal lengths of the various zones do not differ by more than a very few millimetres. The reflecting surface consists of pure silver, deposited chemically on the back of the glass. This is strengthened by a layer of electrolytically-deposited copper, and further protection is given by a coat of special heat-resisting paint. For military and naval purposes the back of the mirror is often covered by a closely applied layer of sheet-lead, held in place by wire netting strained over it. Such mirrors are particularly resistant to damage by oil fumes or noxious gases, and will remain serviceable even after being pierced by a rifle bullet.

Mirrors with double curvature, the vertical section being parabolic and the horizontal section hyperbolic, were made by Parsons in very early days. These produce a flat diverging beam of light, and were first used by vessels navigating the Suez Canal, to light up the buoys on each side of the fairway. They were of 20 in. diameter and a focal length of 10½ in., and gave a flat beam with a divergence of 12°. By their use, the necessity for the employment of a diverging lens was obviated. Subsequently these double-curvature mirrors were made in two halves hinged together as shown in Fig. 15, so that either a single beam of 12° divergence could be obtained, or two beams of 6° divergence separated by a dark space. The object of this type of mirror was to avoid dazzling the pilot of an oncoming vessel, while maintaining the light on the buoys at the side of the canal.

In another type of double-curvature mirror devised by Parsons, the vertical section is parabolic, and the horizontal section elliptical. Mirrors of this kind project a beam which first converges to a vertical line, and subsequently diverges. They have been supplied in large quantities for military searchlights, as the beam can be make to pass through a narrow loophole and diverge beyond it. The searchlight may be thus almost completely protected from injury by rifle fire. Time does not permit me to describe the many other types of reflectors made at Heaton for use in connection with cinematography, the lighting of aerodromes, lighthouses, etc.

OPTICAL GLASS AND TELESCOPES

Another result of Parsons' interest in optical work was his acquisition and reorganization of a factory for the manufacture of optical glass. Before the War there was only one works in this country making optical glass, most of our requirements being purchased abroad. When War broke out the situation was serious, and to render the nation independent of foreign supplies the Government made arrangements for the establishment of an optical-glass works near Derby. After the War was over and the post-war slump had begun, it seemed probable that the optical-glass works would be shut down, and a valuable asset thus lost to the country. Parsons therefore stepped into the breach, and after some negotiations purchased the whole factory in 1921.

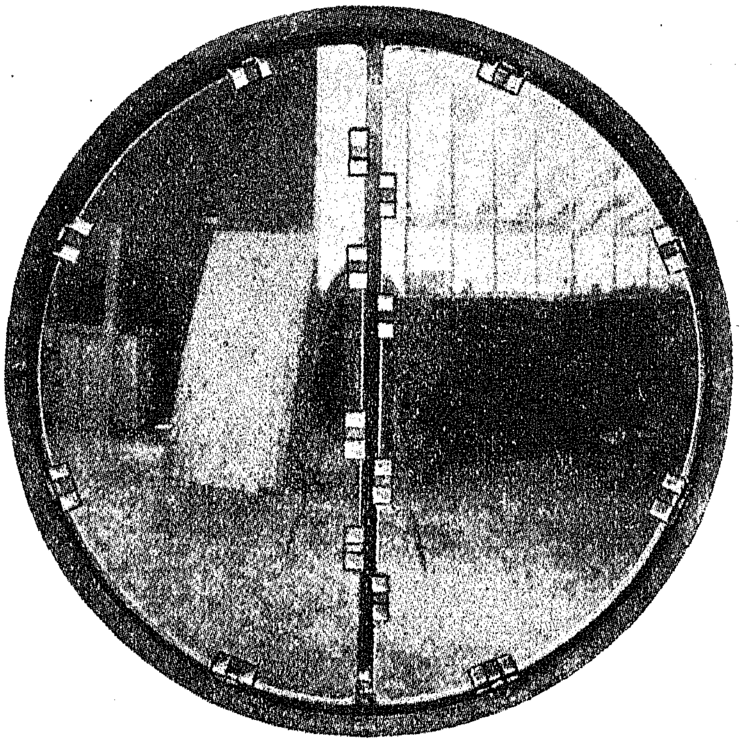

Fig. 15.—Suez Canal mirror.

He at once set about improving the processes of manufacture. The old method was to melt the glass in a pot, breakage of which caused the loss of much glass. Moreover, when breakage did not occur, wastage was caused by the practice of allowing the glass to cool in the pot and to be broken into pieces which afterwards had to be moulded. Parsons introduced new and better methods of heating the pots so as to avoid breakage, and also improved the method of stirring the molten glass. Furthermore, instead of allowing the melt to cool in the pot, he caused it to be run into a mould and taken direct to the annealing furnace, to which he made many improvements. In consequence he was able to make perfect discs of optical glass up to 72 in. diameter and 7 in. thick, and to produce them from glasses having various properties—indeed, about 100 different kinds of glass were made at Derby. By his public-spirited action Parsons saved the factory and contributed greatly to the reputation which English optical glass now enjoys, but he made no money by it and it is said that this enterprise cost him £60 000. After his death the factory was taken over by Messrs. Chance Brothers, of Birmingham.

Parsons was equally enterprising, but more fortunate, in his acquisition of the optical works of Sir Howard Grubb in 1925. These works, which had been moved from Dublin to St. Albans during the War, were threatened with closure. Parsons acquired them, and formed a new firm under the name Sir Howard Grubb, Parsons, and Co., to continue their activities. This he established in new buildings at Walker Gate, close to the Heaton Works, to which it is now affiliated. Here the manufacture of large astronomical telescopes and other apparatus for which Sir Howard Grubb's works had been famous, is carried on with the greatest success. The heavy machine work required in the construction of large telescopes is carried out in the Heaton Works, the proximity of which is a great advantage. Some very important telescopes have been built at Walker Gate, the largest being an instrument with a diameter of 74 in. recently erected at Toronto. This is at present the largest telescope in the British Empire, and the largest but one in the world, and another of the same size is being made for Pretoria in South Africa.

Another of Parsons' enterprises in connection with optical matters was the acquisition, in 1921, of a controlling interest in the firm of Messrs. Ross, Ltd., of Clapham Common. Messrs. Ross, as is well known, are important makers of binoculars and other small optical apparatus of the highest class, and the requirements of this business undoubtedly influenced Parsons in his decision to take over the optical-glass works at Derby, as already mentioned.

EXPERIMENTS ON THE MANUFACTURE OF DIAMONDS

The question of the origin of diamonds always had a fascination for Parsons, and it was probably about 1886 that he carried out his first experiments with a view to making diamonds artificially. His plan then was to try to melt carbon under a very high pressure, by means of an electric arc in conjunction with a hydraulic press. He also tried crystallizing carbon by the solidification of molten iron, but the results of his experiments were negative.

He returned to the problem about 1906, and put up a special building in the Heaton Works to house a 2 500-ton hydraulic press, and a storage battery capable of giving 50 000 amperes. Great precautions were taken against accident, and nobody was ever hurt. As a measure of safety the part of the building containing the press was separated from the remainder by a partition with an iron door, and the roof was made very light so as not to confine an explosion. On one occasion I heard a loud bang and saw a column of smoke and debris. I called one or two men, went to the press-house, and found Parsons standing calmly outside and surveying the wreckage, which was largely confined to the roof. He was very indignant that we should have left our work to come to his assistance.

Most of his experiments on the melting of carbon were carried out at pressures from 30 to 50 tons per sq. in., but in some instances 75 tons per sq. in. was reached. Currents up to 50 000 amperes were normally employed, although 80 000 amperes were sometimes obtained by short-circuiting. None of the several hundreds of experiments designed to melt or vaporize carbon under pressure showed more than a suspicion of crystallized carbon in the residue, and even so it was almost certainly not pure carbon, but some form of carbide. Parsons also installed an air-pump and carried out experiments in a vacuum, but with no better result. The same has to be said of a series of experiments in which a rifle bullet was fired through the vaporized carbon of an arc into a hole in a block of steel. By this means he could apply a momentary pressure of some 2 000 tons per sq. in. to carbon initially near its melting point and raised greatly in temperature by adiabatic compression.

Parsons spent something like £20 000 on these and other experiments in the manufacture of diamonds, and he once remarked to me: " We have now made a bit of money and deserve to have some fun." Unknown to him, the late Sir Richard Threlfall, F.R.S., was also experimenting on the same subject. Threlfall met Parsons one day and, after telling him of his work, said: " Parsons, I do not mind telling you that my diamonds are graphite." " So are mine," replied Parsons. Moissan, the great French chemist, had also been trying to make diamonds, and the general belief now is that he was equally unsuccessful.

During the experiments on the production of diamonds by means of high pressure, it was observed that in many instances considerable volumetric compressions of liquids were obtained, and as the apparatus, with its 2 500-ton press, seemed very suitable, it was decided to make measurements of the compressibility of liquids at higher pressures than had previously been attempted. Many previous investigators had made tests of compressibility, notably Amagat, who had determined the coefficients of compressibility of water and ether up to 3 000 atmospheres. Parsons determined to extend the range, and secure data up to about 40 tons per sq. in., or double the pressure reached by Amagat. The work was commenced about 1908, and continued for 3 years.

The principal part of the apparatus was a steel mould of 12 in. external diameter, with a 4-in. hole in which the plunger worked. The metal was 40-ton gun steel, and though higher pressures might have been obtained by the use of special steel, this was not considered worth while. The compression of the plunger and packing, and the expansion of the mould, were determined by first making tests with 2 000 cm^3 of water in the mould, and then with 1 000 cm^3 and a steel cylinder of equal volume. The effect of friction was eliminated by taking readings with rising and falling pressures. A pressure of 6 000 atmospheres, or nearly 40 tons per sq. in., reduced the volume of 2 000 cm^3 of water at 18° C. to 1 700 cm^3

Nearly the same reduction of volume was obtained with heavy cylinder oil, having a density of 0·89 at 20° C.

The volume after the release of the pressure was compared with the initial volume, and was found to be slightly less, although there were no signs of any leakage. The reduction of volume could be accounted for by the fall of temperature due to the adiabatic expansion of the liquid. By the use of an accumulator, the pressure could be put on and released rapidly, and by quickly removing the ramhead it was possible to insert a sensitive thermometer immediately after the release of the pressure. All attempts to determine the temperature under high pressure by electrical means were unsatisfactory. Using the thermometer method, it was found that when water having a volume of 870 cm^3 at 40° C. under a pressure of 4 550 atmospheres was allowed to expand adiabatically to atmospheric pressure its volume increased to 1 000 cm^3 and its temperature fell simultaneously to 27° C. The increase of volume was thus 130 cm^3 and the fall of temperature 13 deg. C. The external work done can only account for part of the drop in temperature, and the disappearance of energy is equivalent to the work that would be done by the expansion of the water against an internal tensional force averaging 2 150 atmospheres. Similar experiments were carried out with ether and paraffin oil.

EXPERIMENTS WITH FLYING MACHINES

In 1893 Parsons was experimenting with a model steam engine the cylinder of which was placed inside the boiler, to prevent condensation. The results seemed so good that he made an engine of this type and attached it to a helicopter, to see whether the engine could lift itself into the air. The machine, which is shown in Fig. 16, proved able to lift itself several yards off the ground. The boiler, which was of $2\frac{1}{2}$ in. diameter, 14 in. long, and only from 0·01 to 0·015 in. thick, was turned from a steel bar. The turning of it nearly drove the foreman turner wild. The cylinder, which was single-acting with a bore of $1\frac{1}{4}$ in. and a stroke of 2 in., was machined in a similar way. It was provided with a piston valve of $\frac{5}{16}$ in. diameter which cut off steam at three-quarters stroke, and was arranged inside the boiler. The total weight of the engine was $1\frac{1}{4}$ lb., including 3 oz. of spirits of wine. The latter was evaporated in the boiler, and after passing through the engine was burnt under the boiler. Under these conditions evaporation took place with great rapidity, a rate equivalent to 120 lb. per sq. ft. per hour being obtained. At 1 200 r.p.m. the engine developed $\frac{1}{4}$ h.p. The boiler pressure was about 50 lb. per sq. in., but no pressure gauge was fitted. No very high pressure could be used, as some parts were soft-soldered and others brazed. It may be mentioned that soft-soldered joints will stand up to the temperature of steam at 70 lb. per sq. in., and with spirits of wine would probably stand a higher pressure.

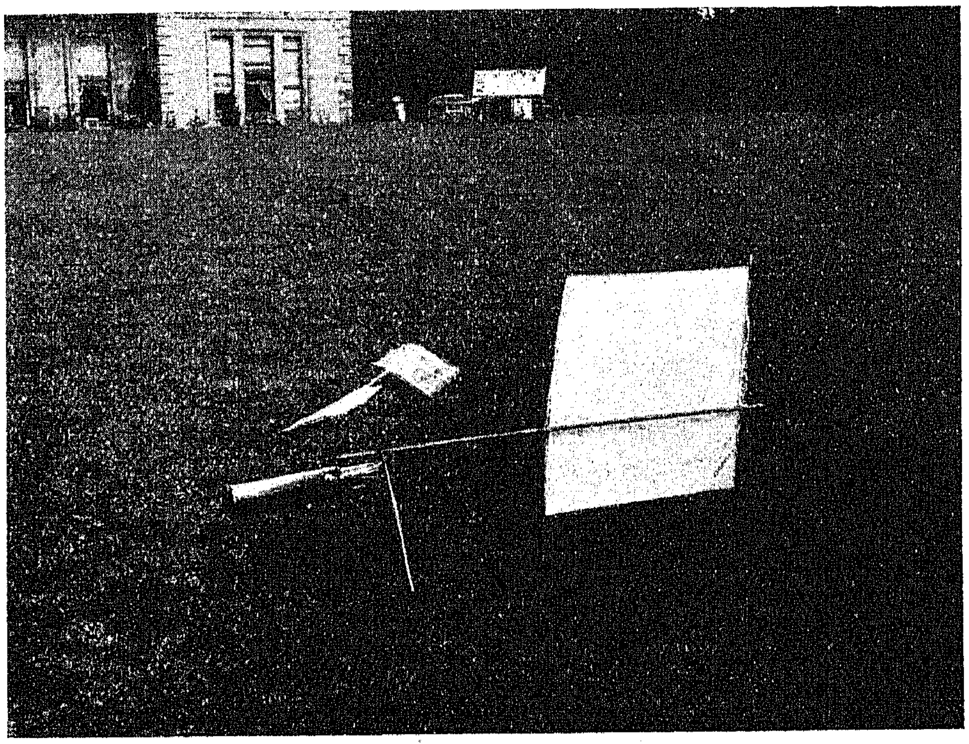

Fig. 16.—Model helicopter driven by steam engine.

After the success of the first experiments the machine was rebuilt, as a monoplane with a framework of cane, and a tail. The wings had a span of 11 ft., the total supporting area was 22 sq. ft., and the total weight $3\frac{1}{2}$ lb. The machine flew about 80 yards and rose to a height of about 20 ft. Fig. 17 (see Plate 2) shows it in flight. This photograph was taken late in the evening, and as the camera had to be swung round to follow the aeroplane, the trees in the background are blurred. It is a great pity that no photograph exists of the machine at rest, and nothing is now known about the details of its construction. As it had no landing-carriage, repairs were always necessary after a flight.

The same engine, or possibly a similar one, was afterwards fitted into a carriage with wire wheels (Fig. 18 on Plate 2), called " The Spider," which ran about the lawn at a great rate. A smaller machine of the same kind used to run about the library, spitting out burning spirits of wine as it went. I can well remember Parsons and his children running after it and stamping out the flames on the carpet. The furniture also suffered from these experiments.

THE AUXETOPHONE

About the year 1902, when phonographs and gramophones were becoming popular, Parsons realized that their reproduction of sound was far from satisfactory. The reason for this was seen to be that the diaphragms and sound-boxes were imposing their own characteristics on the sound waves, and thus causing indistinctness and distortion of the voice or music reproduced. He therefore decided to make a reproducer worked by compressed air, known later as the Auxetophone, by which the sound waves should be generated more in accordance with the action of an organ pipe than with that of a telephone receiver. The essential feature of his idea was to form the sound by causing the needle of the gramophone to operate a valve which should control the emission of the air in exact accordance with the grooves of the record. The valve would thus be the mechanical equivalent of the vocal chords in the human throat. Something of the same kind had been proposed by Edison in 1877, and other inventors had suggested the use of air-relays, but so far as is known no practical instrument on this principle had been produced.

Parsons commenced by making careful experiments on the flow of air through small orifices, and discovered, amongst other things, that for openings of less than 0·001 in. the viscosity of the air altered the characteristics of the flow. He saw the necessity of having a very light valve with a large lip area and a small movement, in order to reduce the acceleration forces to the minimum. In this connection it may be mentioned that the acceleration force on the needle of a gramophone playing loud music having a sound-wave frequency of 500 cycles per sec. is about 40 times the weight of the needle, and the amplitude of its motion is only about 0·003 in.

Although this was a period of intense development of the turbine and turbo-machinery in general, Parsons began to devote most of his leisure to the new problem he had set himself to solve, often working until the small hours of the morning in his private workshop at Hollyn Hall, near Newcastle, where he lived. At first the models were crude, made from tobacco tins, watch springs, pieces of bone, india-rubber bands, and indeed anything at hand that could be made to serve. Sealing wax was largely used in their construction, for Parsons had a great belief in this substance for experimental work, and could do wonders with it. Later he procured a complete set of watchmakers' tools, and, being an excellent workman, he produced valves of which any instrument maker might have been proud. Valves of the grid-iron, slide-valve, and piston type were all tried and rejected, as particles of dust were found liable to cause them to stick, even when the air was filtered. Furthermore, if such valves fitted loosely enough to give free motion, the leakage was so great that the air discharged was no longer proportioned to the movement of the valve, and the quality of the sound was therefore impaired. Parsons possessed an excellent ear for music, which was a great help to him in these investigations.

The type of valve finally adopted is shown in Figs. 19 and 20 (see Plate 2). The moving part was a flat comb of magnalium, the tongues of which were arranged each to cover, with a very small overlap, a corresponding number of rectangular openings in the metal seating. The size of the valve was only $\frac{1}{2}$ in. × $\frac{3}{4}$ in., but the length of lip was as much as 13 in. Air at a pressure of about 2 lb. per sq. in. was supplied by a pump having a capacity of about 5 cu. ft. per minute. The pump delivered the air through a flexible tube to the wind-box, where it was filtered through gauze and cotton wool, before passing to the valve. The latter was mounted rotationally on a pair of torsion-springs in such a manner as to move in a direction substantially normal to its seating. It was operated indirectly from a similarly mounted member which carried the gramophone needle, the connection between the two being a piece of wire passing loosely through holes in each. The wire was surrounded by a viscous liquid, consisting generally of bicycle-tyre cement and oil, which served to eliminate the scratching noises that were liable to occur with the records of that time. A spring, controlled by a piston in a cylinder connected to the wind-box, enabled the closeness of the valve to its seat to be adjusted. This adjustment was important, as it was essential that, even with the loudest notes, the valve should not touch the seat, for otherwise " blasting " occurred.

The valve, complete with its box, was mounted on a right-angled T-piece at the end of a tapered tubular arm which was pivoted to the horn. A balance weight was provided to reduce the pressure of the needle on the record. The T-piece gave a sharp right-angled turn to the sound path, and, aided by an adjustable hollow plunger filled with cotton wool, acted as an additional scratch filter and suppressed unpleasant harmonics.

Such a valve, made 35 years ago, reproduced sound with a volume and quality which have only recently been equalled by wireless loud-speakers and electric gramophones. Parsons often used to operate an Auxetophone on the terrace at Hollyn Hall, and it could be heard all over the village $\frac{1}{2}$ mile away. I myself also used to play one through the side door of my house, and the attraction was so great that on one occasion the police had to clear the crowd away.

When patents were applied for, in 1903, it was discovered that the late Horace Short had already patented a valve working on a similar principle. Parsons purchased Short's patent, and engaged Short, who was a wonderful mechanic, to develop the Auxetophone at Heaton Works. After a time the patent for the use of the valve on a gramophone was sold to the His Master's Voice Co., and the next object was to apply it to the amplification of the sound of musical instruments. This aim was successfully achieved in the case of the 'cello and the double-bass fiddle, but the apparatus was too cumbersome for its convenient use with an ordinary violin. Cellos and double-bass fiddles fitted with Auxetophones were used with success in Sir Henry Wood's orchestra at the Queen's Hall in 1906, but they had to be given up as the musicians objected to one instrument doing the work of four or five.

So far as gramophones were concerned the Auxetophone never came into general use, largely on account of its cost and the necessity of a motor and air pump to supply the air, and also because it needed more attention, in the way of taking apart and cleaning, than the average user was likely to give it. No matter how carefully the air was filtered, dust always collected and had to be cleaned out. The Auxetophone might have found a future in cinematograph work, but by the time this had become a possibility the patents had expired, and all chance of a monopoly, which would have justified further expenditure on development, had gone. About 15 years ago, when broadcasting commenced, the Auxetophone was used in conjunction with a Brown telephone, and gave results superior to those given by the loud-speakers of that day, but the development of moving-coil loud-speakers put an end to prospects in that direction.

PARSONS AND THE BORE-HOLE

In his Presidential Address to the Engineering Section of the British Association at the Cambridge meeting of 1904 Parsons made the suggestion that very valuable geological and mineralogical information might be obtained from a very deep hole in the earth. The deepest mine descends for about 1 mile, but Parsons proposed to go to a depth of 12 miles. He estimated the cost at £5 000 000, and thought that the work would require 85 years for its completion. A temperature of about 272° F. would probably be encountered, and cooling would have to be effected by refrigerating machinery. Air locks would also have to be provided at every 2–3 miles down the shaft, as at this depth the atmospheric pressure would be approximately doubled. He had considered the whole question in detail, and indicated fully the methods by which the work could be carried out. He pointed out, however, that under existing laws the explorer would have no rights or monopolies over any minerals except such as lay beneath the land he might possess at the surface, and it was also doubtful whether he could obtain any patent of substantial value for his methods of boring to great depths. There was the further drawback that any patent would have expired long before the hole was completed. He might have added that everyone connected with the commencement of the enterprise would also have expired before that time! For these and other reasons, there is little temptation for anyone to finance such a project. Parsons again referred to the idea in his Presidential Address to the British Association at Bournemouth in 1919.

EXPERIMENTS ON THE SILENCING OF GUNS

Parsons made many experiments with the object of devising means of reducing the noise produced when a gun is fired. In connection with this work he fitted an expansion chamber, which had a hole for the bullet to pass through, to the muzzle of a rook rifle. This was very effective in reducing the noise of the explosion, but for some reason he did not carry the matter further.

CONCLUSION

In this brief review I have endeavoured to give, however imperfectly, some idea of the less well-known activities of one who was probably the greatest engineer of our time. The outstanding work of his life was the development of the steam turbine and the high-speed electric generator, and his remarkable achievements in this connection must always remain his principal claim to fame. But in spite of the stress of this work, and its enormous demands on his energy, he found time and opportunity to apply his mind to many problems of a widely different nature, and in all of them he showed the same genius, courage, and skill.

Furthermore, it was not only in engineering and scientific work that he shone. He was an all-round man and a thorough sportsman. At Cambridge he pulled a good oar, and in his younger days he followed the hounds. He was a first-class shot, and an accomplished fisherman.

SOME ASPECTS OF MAGNETIC RECORDING AND ITS APPLICATION TO BROADCASTING

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SUMMARY

This paper presents a somewhat simplified consideration of the processes occurring in the magnetic recording of sound on steel tape, and describes some of the apparatus and methods used in this country in its application to broadcasting.

A brief historical account is given of the early uses of magnetic recording. The essential processes involved are then discussed in a simplified form, and the effects of the finite longitudinal spread of the recording field, and of the self-demagnetization of the tape, are considered before the question of background noise is introduced.

In the next section certain fundamental experiments are described, followed by a brief account of various possible methods of saturating, recording, and reproducing. Considerations relating to the conditions for the optimum working of any particular arrangement are put forward, with the results of tests of two of those which are now in use. Some details are given concerning the tape itself, after which a recording machine is described.

The paper concludes with a short account of the technical and programme service requirements for a recording system for use in connection with broadcasting, and a description of a recording channel at the British Broadcasting Corporation's premises at Maida Vale.

SECTION (1)

Introduction

Very little information has been published in this country on the subject of magnetic recording on steel tape. The object of this paper is to give an outline of the theory, and to describe some of the methods and apparatus that have been developed by the British Broadcasting Corporation and Marconi's Wireless Telegraph Co. during recent years.

A certain amount of the elementary theory has been given in previous papers published in other countries, and some of this ground has been covered again. Apart from this, the scope of the paper is limited to work that has been carried out in this country alone.

The research and development work on the subject is by no means complete, but a standard of performance is now obtainable which enables this system of recording to be extensively used in connection with broadcasting.

History

The process of magnetic recording was introduced by Poulsen under the name of the Telegraphone, and was used in conjunction with his arc system of radio-telegraphy. Telegraph signals were transmitted at high hand speed and were recorded at the receiving station on a steel wire which was driven at a higher velocity when recording than during the subsequent reproducing process. Thus the signals could be transcribed by the receiving operator at a convenient speed. In this application, variations in the velocity of the steel wire, and the effects of frequency or amplitude distortion, were relatively unimportant. The recording and reproducing electromagnetic systems were somewhat crude when compared with present-day apparatus, but even at the early date of 1900, when the system was developed, Poulsen clearly proved the possibilities of the magnetic recording of sound, although suitable amplifiers employing thermionic values were not available.

About the year 1924 a German engineer, Dr. Stille, commenced his research on the subject. His work was entirely devoted to the problems associated with the recording of sound, and he made a careful study of both the electromagnetic and the mechanical problems involved. The greatest advantages accruing from Dr. Stille's work were, first, the introduction of steel tape instead of wire, which overcame certain magnetic and mechanical difficulties, and, secondly, the development of an electromagnetic system which resulted in a reduction of wave-form distortion.

The development of magnetic recording in this country dates from the year 1930, when the British Broadcasting Corporation first tested the system under the name of the Blattnerphone. It was soon recognized that, in order to attain a standard of recording suitable for broadcasting purposes, the general performance of the equipment would have to be considerably improved. Experimental work was carried out in collaboration with British Blattnerphone, Ltd., and this resulted in a marked improvement in the quality of reproduction. When the Empire broadcasting service was inaugurated, the system proved to be very useful for recording extracts from the home programmes for subsequent reproduction in the Empire transmissions. The first important programme to be radiated to the Empire by this means was that of Christmas Day, 1932, which included the speech of His late Majesty King George V.

Early in 1933 Marconi's Wireless Telegraph Co. designed a machine in which many of the mechanical difficulties experienced with earlier models have been overcome. Development work has been carried out by both the B.B.C. and the Marconi Co.; this has resulted in a further considerable improvement in the performance of the system.

Fundamental Processes

The process of magnetic recording depends fundamentally upon two properties of steel; remanence and coercivity. It is by virtue of the property of coercivity that neighbouring elements in a length of steel can be magnetized, to a great extent, independently.

Magnetic recording in its simplest form can be carried out by passing a length of steel tape or wire at constant velocity through an electromagnetic device (a recording head) which will produce variations in the distribution of remanent flux along its length.

Reproduction can be effected by passing the magnetized tape at an identical velocity through a device (a reproducing head) which is sensitive to changes of the flux in the tape. The spatial variations of flux will then be transformed into alternations of e.m.f. with respect to time. In the ideal case these correspond to the original alternations applied to the recording head.

It is necessary that any previous variations in the flux distribution in the tape should be removed before recording. This can be done by passing the tape through a " wiping head," which magnetizes the tape to saturation.

The essentials of the system are thus:—

(1) A length of steel tape driven at constant velocity.
(2) A wiping head.
(3) A recording head.
(4) A reproducing head.

In the simplest case the heads might take the form of coils wound round the tape, but if consideration is given to the wide field distribution associated with such coils it is clear that it would be impossible to obtain satisfactory results with practicable tape velocities, except at very low frequencies. It is therefore necessary to introduce a medium of high permeability into the system in order to concentrate the field.

The heads designed to perform these various functions are similar in appearance and construction; they are shown in Figs. 19 and 20 (Plates 1 and 2). Each head consisists of two similar blocks of insulating material held together by a hinge at the back. When closed a slot is formed for the tape to pass through. In each half a strip of magnetic alloy known as a " pole piece " may be placed, making mechanical contact with the tape when the head is closed. The pole-pieces are at right angles to the plane of the tape and are surrounded by coils through which they are free to slide, the pressure of the pole-pieces on the tape being adjusted by spring-loaded plungers. One half of the head can be moved in relation to the other, in the direction of the movement of the tape, so that a variable longitudinal gap is formed between the two pole-pieces.

The wiping, recording, and reproducing heads used in the experiments described have different types of coils and pole-pieces, but are in other respects identical.

The tape may be magnetized longitudinally or transversely, through its width or through its thickness, or in any combination of these directions. It is generally accepted that transverse magnetization of the tape through its width gives inferior results. This paper is concerned essentially with longitudinal magnetization, though it is inevitable that there will also be a transverse component through the thickness of the tape.

It is convenient in the first place to consider the various processes in a simplified form. Let it be assumed that the whole width of the tape is used, and that at any point in its length the flux distribution is substantially uniform over the cross-section.

The wiping head carries a direct current adequate to saturate the tape completely, so that it leaves the head fully magnetized, i.e. with the maximum remanent induction ($B_{r\,max.}$) in a longitudinal direction.

The Recording Process.

The object of the recording head is to produce variations in the flux in the tape of the largest amplitude that is consistent with linearity. It will be shown that the alternating current representing the programme to be recorded must be superimposed on a direct current, the purpose of which is to bring the tape to a suitable magnetic state. It is also necessary for the net current in the head to produce a field that is always opposed in direction to that of the wiping head or partial rectification may occur. For this reason the direct current in the recording head is usually referred to as the demagnetizing current.

Each elementary length of tape passing through the head will be demagnetized to an extent which is largely dependent upon the net value of the alternating and the steady components of the field acting upon it, and will leave the head with a corresponding value of remanent induction (B_r). If the recording current is sinusoidal, of frequency f cycles per sec., and the tape speed is u, variations in the flux in the tape will be produced of wavelength given by

$$\lambda = \frac{u}{f}$$

The process may be followed by referring to a $(B - H)$ curve for the tape (Fig. 1). An elementary length of tape enters the wiping head in some unknown condition, and is then brought to saturation (point 1). It leaves the wiping head fully magnetized (point 2) and is then subjected to the recording field. If, at this moment, the sinusoidal a.c. component is zero, the effect of the d.c. component is to reduce the magnetization to a state corresponding to point 3, and on leaving the head the remanent magnetization is represented by point 3a. The effect of the a.c. component is to increase and decrease the effective value of the demagnetizing current. If the a.c. component is at either of its peak values the tape is demagnetized to a degree represented by points 4 or 5, and leaves the head in a state corresponding to points 4a or 5a. Point 3 may be called the working point, and its position is determined by the state of the tape as it enters the recording head, and by the value of the d.c. component of the demagnetizing current.

It is important to realize that the whole of the tape is not subjected to an alternating cycle, but that each elementary length of tape is demagnetized separately to a degree depending upon the net demagnetizing current, so that the tape leaves the head with a value of B_r (the remanent induction) which varies sinusoidally along its length, provided that there is a linear relation between the demagnetizing current and B_r. Referring again to Fig. 1, this implies that, in this simplified consideration, variations in induction represented by points 4a, 3a,

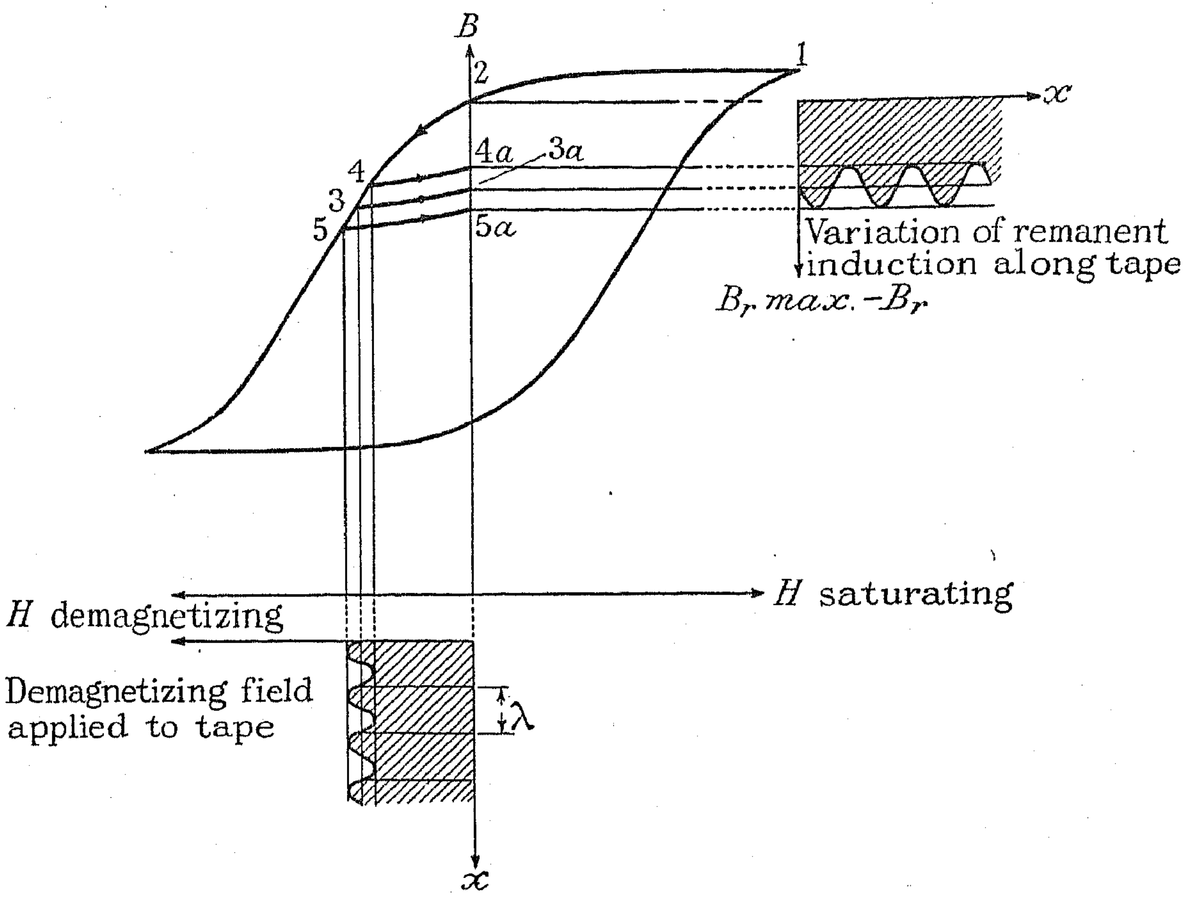
B
1
2
4a
3a
4
3
5
5a
x
Variation of remanent induction along tape
B_r max. $-B_r$
H demagnetizing
H saturating
Demagnetizing field applied to tape
λ
x

Fig. 1.—Simplified recording process.

and 5a (rather than 4, 3, and 5), should be proportional to the corresponding values of the demagnetizing current. Now in order that points 4, 3, and 5, should have a linear relationship to the demagnetizing current through as wide a range as possible, the largest possible hysteresis loop must be used. In other words, the tape should enter the recording head fully magnetized. In practice, it appears that this condition also fulfils the requirement that the range through which the remanent magnetization is linear with the demagnetizing current should be a maximum. The optimum value of the d.c. component of the demagnetizing current to give the maximum variation of remanent flux with minimum distortion can be found empirically.

Let it be assumed that the variation of longitudinal flux in the tape after it has left the recording head is sinusoidally distributed along its length. Any variation in the flux in the tape implies that a corresponding number of lines of magnetic induction enter or leave the tape. These lines may be termed the external flux. It follows that the surface density (B_s) of external flux at any point in the length of the tape is proportional to the rate of change of the flux along the tape at that point. This surface flux density is independent of the mean state of magnetization of the tape, which is the datum about which variations take place, and which is determined by the d.c. component of the recording field. There is one value of this component for which variations will occur about the state of zero longitudinal magnetization as a datum, but in practice a somewhat lower value is used, so that the direction of magnetization in the mean state is the same as that of the fully magnetized tape.

In this consideration it may be assumed that the value of this datum has no effect upon the external flux distribution, and it is taken as being zero. A diagrammatic representation of the longitudinal and external flux is shown in Fig. 2(*b*). The value of the longitudinal induction at any point is given by the width of the shaded area at that point, whilst its direction is given by the white arrow in the centre. If ϕ represents the longitudinal flux in the tape in any section and Φ is the

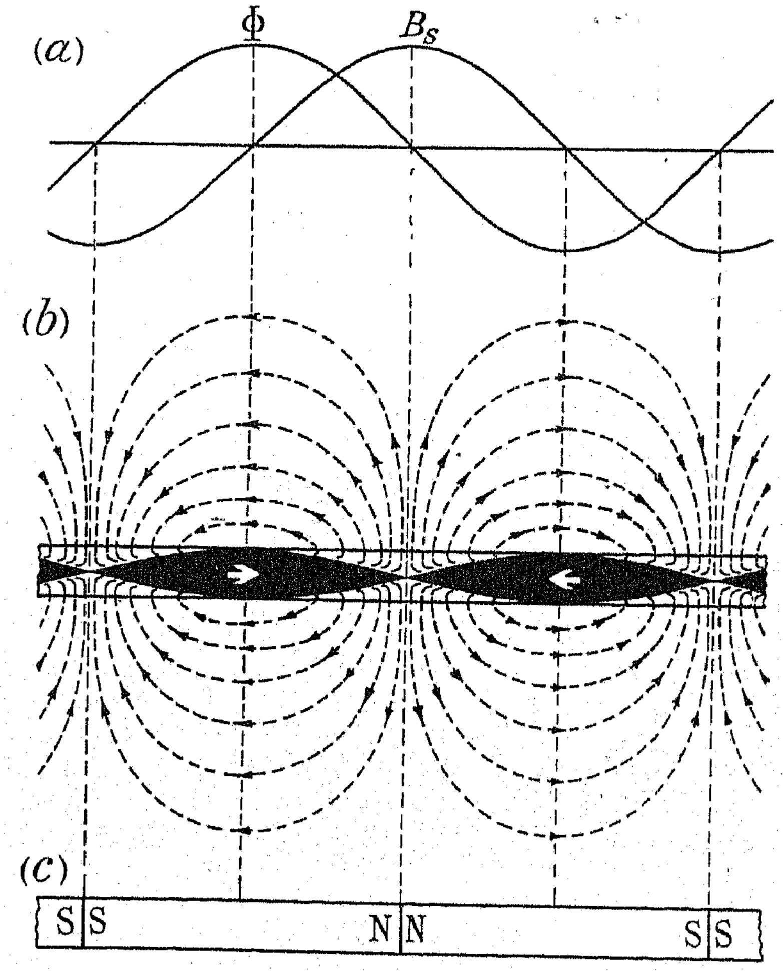

Fig. 2.—Flux distribution for recorded tape.

peak value of this, then $\phi = \Phi \sin 2\pi x/\lambda$, where x represents distance along the tape and the mean surface flux density B_s is proportional to $d\phi/dx$, which is given by

$$\frac{d\phi}{dx} = \frac{2\pi}{\lambda} \Phi \cos \frac{2\pi x}{\lambda}$$

The distribution of external flux is thus in phase quadrature with the longitudinal flux (Fig. 2*a*), and its maximum values are reached where the rate of change of longitudinal flux is highest, though the flux itself is at its datum value. At these points poles will, in effect, be formed on the surface of the tape. From the above expression it will be seen that, for a given value of Φ, the strength of these surface poles is inversely proportional to the wavelength. Since the tape moves with constant velocity $u = x/t$ the rate of change of the flux along the tape can be expressed as a time rate of change of flux passing a given point. Thus

$$B_s \propto \frac{\omega}{u} \Phi \cos \omega t, \text{ where } \omega = 2\pi f.$$

In an ideal case, the external flux passing any given point will therefore vary sinusoidally with time, and the problem now arises of transforming these variations of flux back into variations of e.m.f.

The Reproducing Process.

An examination of the reproducing process is necessarily very complicated, since it should take into account the effect of the pole-pieces upon the flux distribution in and around the tape, for in any system in which pole-pieces are used the external flux distribution of the tape is bound to be somewhat altered by their presence. Fortunately, however, it is not inevitable that the reproduced waveform will be correspondingly distorted. It has already been explained that some form of iron circuit is essential, since the physical dimensions of any coil used for reproducing purposes will be large compared with the wavelength at the higher frequencies. A relatively large coil is, of course, necessary in order that the reproduced e.m.f. should be high compared with the valve noise produced by the first valve of the reproducing amplifier.

The surface poles on the tape due to the recorded signal will induce poles of opposite polarity at the tip of any pole-piece in contact with the tape, and like poles distributed along the surfaces and the far end of the pole-piece. If a coil is wound closely round the pole-piece, a certain percentage of the turns of this will be threaded by the flux that enters the pole-piece, and an e.m.f. proportional to the time-rate-of-change of flux-turns will be generated in the coil.

In the simplest case, for long wavelengths, the flux threading the coil would be proportional to the value of B_s, so that the reproduced voltage would be given by

$$v \propto \frac{dB_s}{dt} \propto \frac{\omega^2}{u} \Phi \sin \omega t$$

As the frequency is increased, however, the percentage of turns threaded is reduced, and, further, the effective magnetic permeability of the pole-piece metal becomes lower. Thus the efficiency of the reproducing system tends to fall off very rapidly as the frequency rises. Furthermore, it is not possible for Φ to be maintained constant throughout the frequency range of the system, owing to the limitations of the recording head and to the effects of self-demagnetization. Thus an overall frequency characteristic that rises steeply as the frequency increases is not obtained, though it might be expected from the above expression for the reproduced voltage.

The simple explanation which has just been put forward serves to give some general idea of the principles of magnetic recording. In practice the recording process is very much more complicated, and, while it would be impossible to give even a qualitative analysis in detail, there are two important factors which deserve consideration.

The first is the effect of the finite longitudinal spread of the recording field, and the second is the self-demagnetizing effect of the surface poles formed by the recorded signal.

Effect of Recording with a Finite Field Distribution.

So far in this consideration the effective longitudinal spread of the recording field has not been taken into account. This must be finite in order to produce variations in the longitudinal flux in the tape. On the other hand, if the effective spread is comparable with the wavelength of the flux variations at any frequency, distortion of the waveform will result.

In order to simplify the explanation of this, an ideal case may be considered, in which it is assumed:—

(1) That the time of magnetization is effectively zero. This implies that the remanent magnetization of the tape after the magnetizing field has been removed is independent of the time during which this field was applied.

(2) That the final state of remanent magnetization in an elementary length of tape that has been saturated and then partially demagnetized depends only upon the peak value of the applied demagnetizing field, so that the subsequent application of a demagnetizing field of a lower value has no effect.

(3) That the value of this remanent magnetization bears a linear relationship to the current in the windings of the recording head, and that each elementary length of tape can be magnetized independently.

(4) That self-demagnetization effects can be neglected.

In the first case, let the spatial distribution of the applied demagnetizing field be rectangular, so that it reaches a maximum value instantaneously, is constant throughout a distance dx measured along the tape, and falls away instantaneously to zero. Let this value vary sinusoidally with time, about an arbitrary datum level.

Referring to Fig. 3, the tape is first of all saturated to state 1, and enters the influence of the recording field in state 2. There will always be a section of tape of length dx which is under the influence of the demagnetizing field. The distortion of the recorded waveform that results from the finite value of dx can best be visualized if it is imagined that an attempt is made to draw a sinusoidal curve with a very broad pen-nib. Although any one point on the nib will trace out a true sine wave, the outer edges of the curve so drawn will not be sinusoidal.

Two curves (A and B in Fig. 3) have been drawn which correspond to the demagnetizing effect of the extreme edges of the field distribution. The boundary curve of the shaded area will then give the peak values of the demagnetizing field which is applied to the tape at any point. The resulting changes in remanent induction ($B_{r\,max.} - B_r$) are shown by curve C, which thus gives the distribution of remanent induction along the tape. Clearly, unless dx is very small compared with the wavelength, so that the boundary curve is approximately sinusoidal, distortion due to even harmonics will occur. This form of distortion is dependent upon frequency and cannot be eliminated by reduction of amplitude. In order to minimize it, the length (dx) over which the field is maintained constant should be small compared with the shortest wavelength.

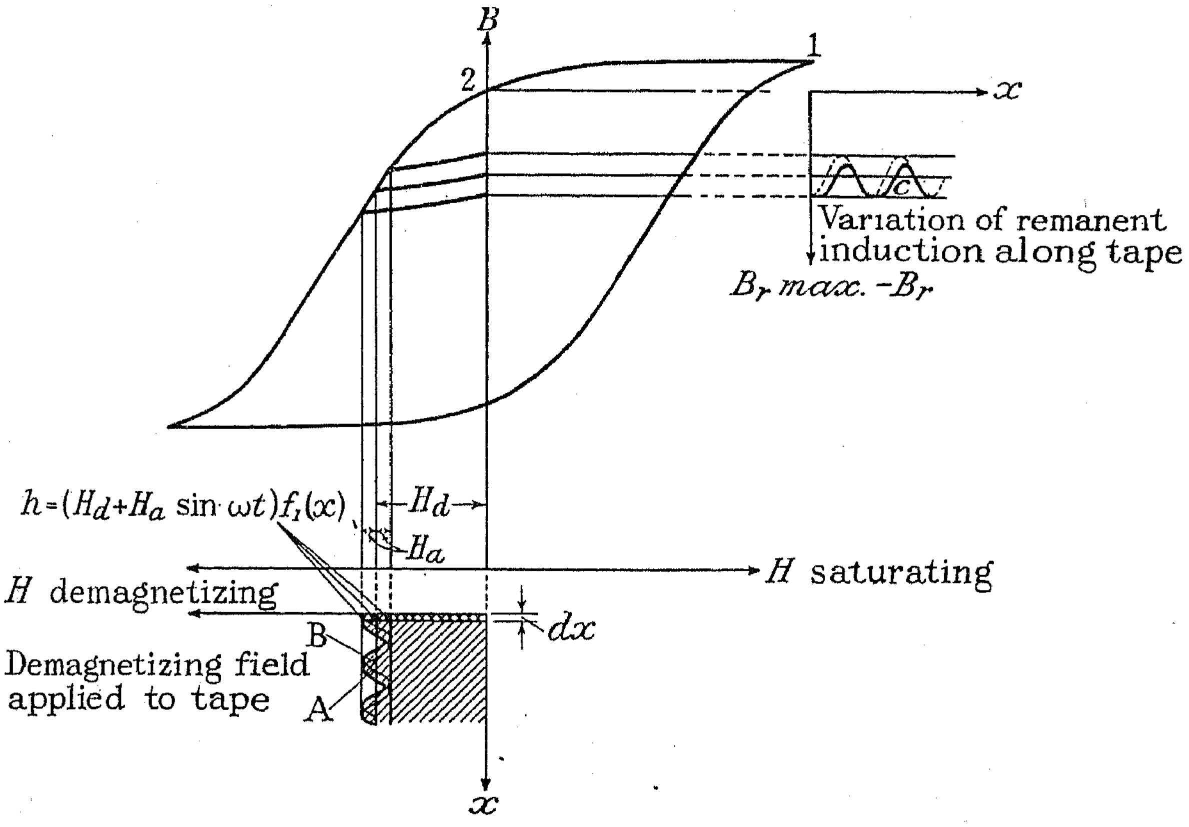
B
2
1
x
C
Variation of remanent induction along tape
$B_r\,max. - B_r$
$h = (H_d + H_a \sin\omega t) f_1(x)$
H_d
H_a
H saturating
H demagnetizing
B
Demagnetizing field applied to tape
A
dx
x

Fig. 3.—Distortion due to recording field distribution. $h = (H_d + H_a \sin \omega t)\, f_1(x)$.

In practice it is not possible to obtain a field distribution that falls away instantaneously to zero along the tape, and a second case will now be considered in which the demagnetizing field rises sharply to its maximum value and falls away upon some arbitrary curve. The value of the field represented by each point on the curve will vary sinusoidally in time about a datum fixed by the value of the d.c. component of the demagnetizing current.

If the field distribution is such that the reduction in field along the tape is not sufficiently rapid, an elementary length of tape which was originally demagnetized by a low value of field may subsequently be subjected to a higher value. Referring to Fig. 4, it will be seen that the boundary curve of the shaded portion indicates the actual peak value of demagnetizing field to which the tape will be subjected at any point in its length, and this will produce a distribution of remanent induction corresponding to curve D. This type of distortion is dependent upon both frequency and amplitude, and can be eliminated by a sufficient reduction of amplitude or increase in the wavelength.

In practice, the distortion due to both these types of field distribution may occur, but since it will be most pronounced at the higher frequencies the most serious harmonics are likely to be outside the useful range of the system. Intermodulation tones due to amplitude non-linearity, however, may still be reproduced.

Effect of Self-Demagnetization.

A length of tape, in which sinusoidal variations of flux have been recorded, can be represented by a series of magnets each half a wavelength long, placed end to end with like poles adjacent, as shown in Fig. 2(*c*). Since the self-demagnetization effect for any magnet increases as the length is reduced, for a constant cross-section, the effective pole strength is reduced as the recorded frequency is increased. With the normal tape speed of 1·5 metres per sec., the wavelength corresponding to a signal frequency of 5 000 cycles per sec. is 0·3 mm., so that each of these magnets will be 0·15 mm. long. As the thickness of the tape is 0·08 mm. and its width 3 mm., the self-demagnetization effect may well be of fundamental importance, especially at the higher frequencies. When this is taken into account, a new condition for amplitude linearity must be introduced. Referring to Fig. 5, the elements of tape which have been demagnetized by the applied demagnetizing field to states corresponding to points 3, 4, and 5, on the hysteresis loop would return to states corresponding to points 3a, 4a, and 5a, if the field acting upon them were reduced to zero. But the statement that there is an alternating external flux distribution about the tape and that, in effect, poles are formed on its surface, implies that the

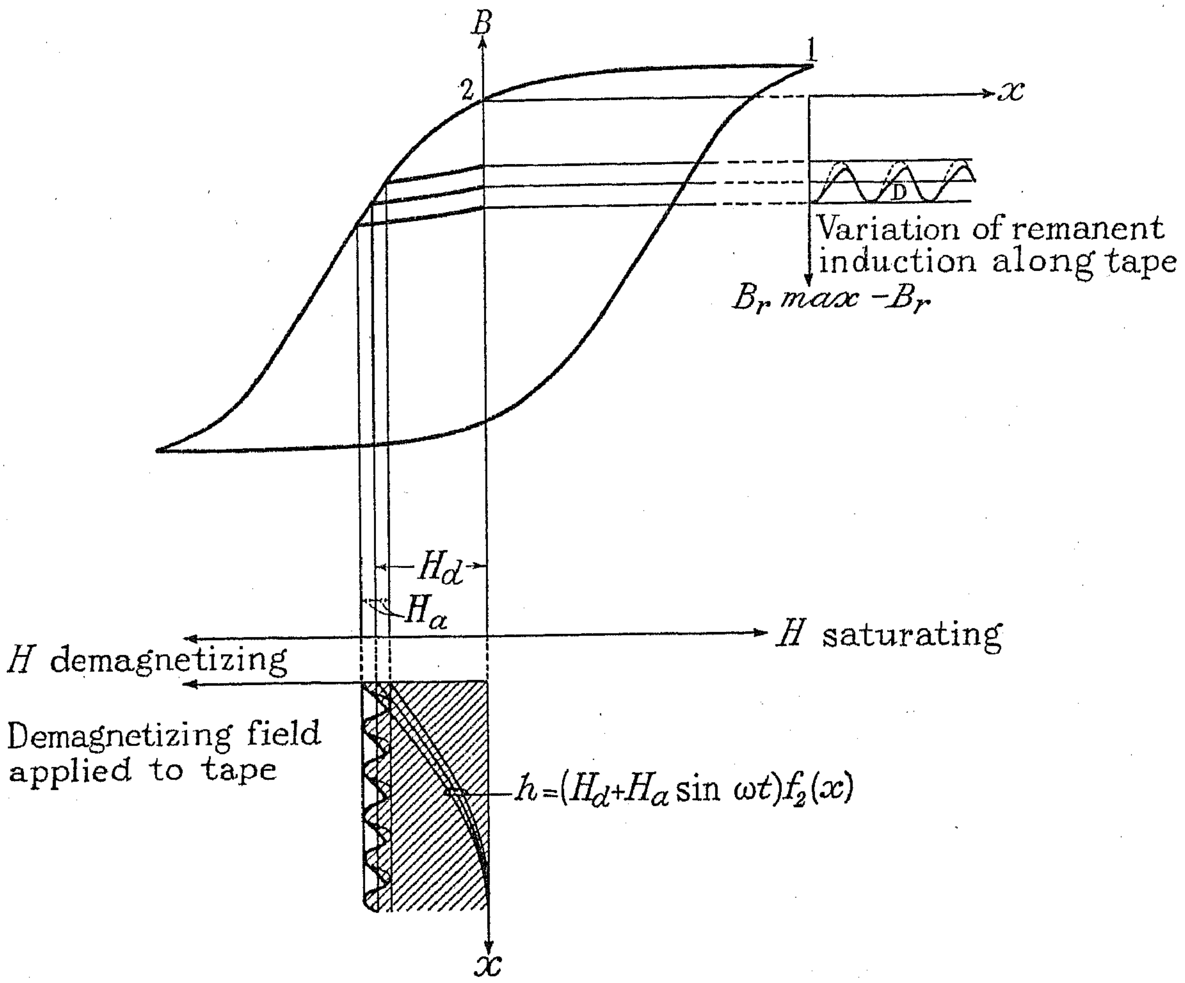
B
1
2
x
D
Variation of remanent induction along tape
Br max −Br
Hd
Ha
H demagnetizing
H saturating
Demagnetizing field applied to tape
h=(Hd+Ha sin ωt)f2(x)
x

Fig. 4.—Distortion due to recording field distribution. $h = (H_d + H_a \sin \omega t) f_2(x)$.

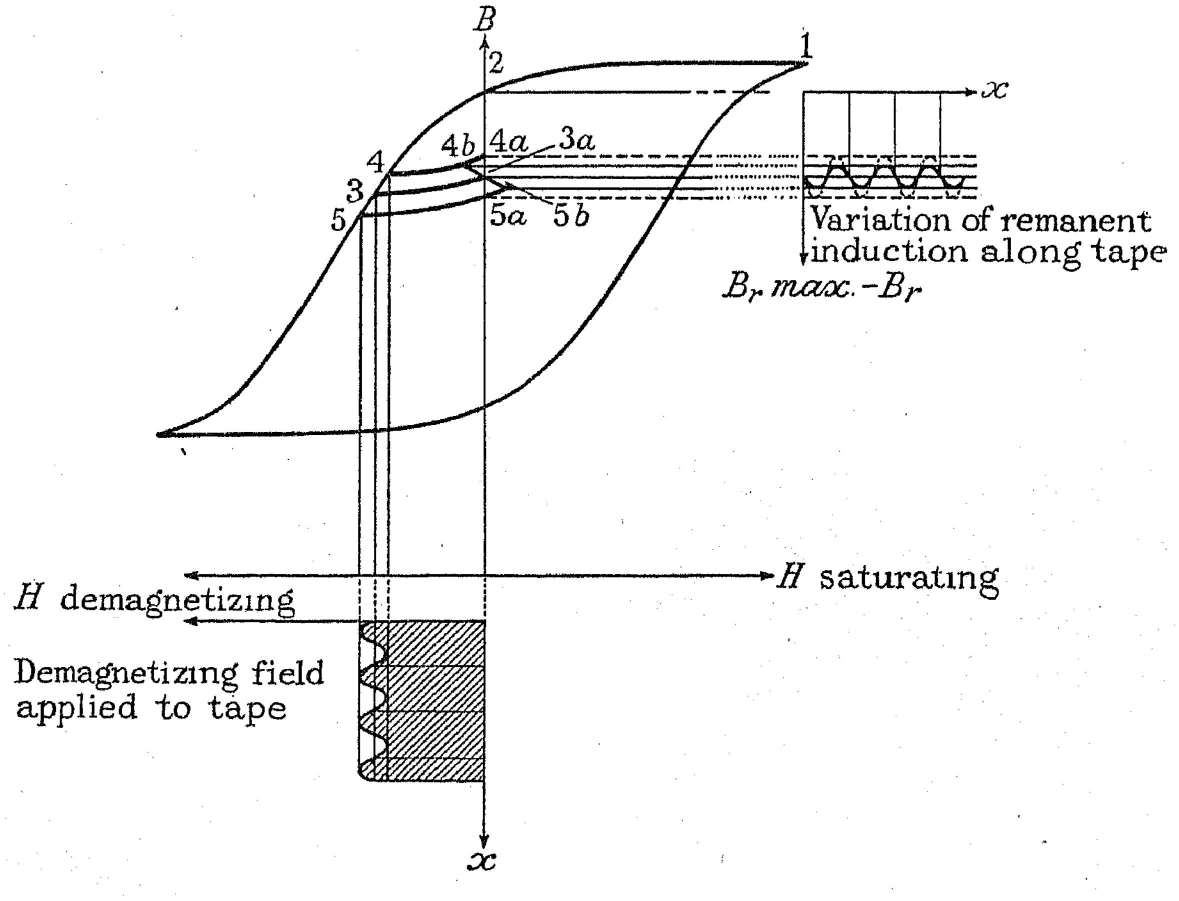
B
1
2
x
4b
4a
3a
4
3
5
5a
5b
Variation of remanent induction along tape
Br max.−Br
H demagnetizing
H saturating
Demagnetizing field applied to tape
x

Fig. 5.—Self-demagnetizing effect in recorded tape.

tape is subjected to a self-demagnetizing field that alternates along its length. It is impossible to differentiate between the effect of this self-demagnetizing field and that of an externally applied field upon an elementary cube inside the tape, so that it becomes necessary to modify the conception of the process represented on a $(B - H)$ characteristic.

The self-demagnetizing force acts in such a direction as to reduce the flux variations about the datum, increasing the demagnetization of the element which was subjected to the minimum recording field, and vice versa. The final points reached will then be 3a, 4b, and 5b, in Fig. 5, rather than 3a, 4a, and 5a. It is possible that for very long wavelengths, where the self-demagnetization is comparatively low, these sets of points may be almost coincident, but for the shorter wavelengths this will not be the case. Assuming a sinusoidal recording current, the new condition to be fulfilled for amplitude linearity in recording is that on the $(B - H)$ curve, point 3a should lie on a straight line midway between points 4b and 5b. From this point of view it would appear that it is even more important that the tape should have high coercivity than that the maximum value of remanent magnetism should be high.

This self-demagnetization effect, which is essentially the effect of the poles formed on the surface of the tape, still further complicates the process of recording. For, at the moment of recording, the tape is subjected to the resultant of the field due to these poles formed by the signal already recorded, and the applied field due to the recording head. For any given frequency the former will be alternating in value and in general will be opposed to, but not in exact antiphase with, the latter. At the higher frequencies these fields may be of the same order of magnitude, in which case the tape is subjected to a considerably lower net recording field than that estimated from the constants of the recording head.

Background Noise.

It can be seen that there are a number of conditions that must be fulfilled in order to avoid distortion in the recording process, and these determine the maximum amplitudes that can be recorded.

A lower limit to the permissible recording level is imposed by background noise, which is inherent in the use of any sound-recording medium yet developed. The reproduced level of background noise is mainly dependent upon the following factors:—

(*a*) Variations in the magnetic and mechanical properties of the tape itself, due to such considerations as granular structure and size, chemical composition, physical dimensions, and surface polish. Since the material of which the tape is composed is a mixture as distinct from an alloy, the above properties will largely depend upon the degree of uniformity which it is possible to maintain during the process of manufacture. Variations in the properties of the tape may also be produced by uneven stresses occurring during the operation of the machine.

(*b*) The mean state of magnetization of the tape leaving the recording head.

(*c*) Relative motion between the pole-pieces and the tape, and between the coils and the pole-pieces. This is largely due to unevenness of the tape surface and to mechanical vibration. It should not cause noise in the case of the wiping pole-pieces unless the final saturating flux is inadequate to saturate the tape completely. In the case of the recording and reproducing pole-pieces, the noise produced will depend upon the magnitude of the motion and upon the resulting change in the reluctance of the magnetic circuit involved.

(*d*) Variations in the magnetic properties of the pole-piece due to vibration when in contact with the moving tape.

(*e*) The relation between frequency and the recorded flux variations. This varies with the recording frequency characteristic used, and affects the noise level because it determines the frequency response of the reproducing amplifier.

(*f*) It is possible that the phenomenon of magnetostriction and the Barkhausen effect may contribute to the noise reproduced, but it is thought that their influence is probably small compared with the other factors enumerated.

It can be seen that the reproduced noise level is very much dependent upon the manufacture of the tape itself, and, while considerable improvement has been made during recent years, it is hoped that yet further improvements may be made in this direction.

SECTION (2)
Static Tests

Before treating the wiping, recording, and reproducing systems in further detail, it may be well to describe certain of the static tests that have been carried out. The term " static " is here applied to tests carried out upon either moving or stationary specimens of tape which do not involve the rate of change of the magnetizing current.

To show the magnetic properties of the tape, tests were made upon ring-shaped specimens. For example, a ring formed by winding 125 turns of tape to a mean diameter of 5 cm. has been used. The thickness of the ring was approximately 1 cm., and as the width of the tape is 0·3 cm. the cross-sectional area was 0·3 cm^2. The magnetizing winding consisted of 300 turns wound toroidally, and a search winding of 50 turns was connected to a fluxmeter.

The core was subjected to a sequence of magnetic fields such as might, in an ideal case, be experienced by a length of tape during the recording process. By observing the readings of the fluxmeter a family of curves was plotted showing the changes in the magnetic state of the tape over the whole range of the $(B - H)$ characteristic (Fig. 6).

The remanent induction retained after any given demagnetizing current has been applied to the saturated tape may be plotted against the field due to this current. Fig. 7 shows such a remanence curve (A) which can be deduced from the results shown in Fig. 6. It is of significance since it indicates the relation, in the static case, between the recording field and the remanent flux in the tape.

It might be thought that very different results would be obtained if tests were carried out upon a length of tape under normal conditions. This point has been examined by threading three coils on a single length of tape running on the machine, the first carrying a steady current adequate to bring the tape to saturation and the second being used to demagnetize it to any required degree. The circuit associated with this coil included a resistance, a switch, and a d.c. source. The third coil was used as a search coil and was connected to a ballistic galvanometer which was calibrated against a fluxmeter. The tape was run through the three coils at the normal speed of 1·5 metres per sec., the demagnetizing coil being unexcited. The switch completing the circuit of this coil was then closed and the change in remanent induction was calculated from the swing of the galvanometer. This was repeated for various values of demagnetizing current. Curve B in Fig. 7 shows the relation between the change of the remanent induction and the demagnetizing field.

The two curves in Fig. 7 show a very reasonable agreement, in view of the fact that the two specimens of the tape used were not necessarily identical in properties. Further, the calculation of the value of the field was only approximate, whilst in computing the values of the induction (B) it was assumed in both cases that the flux was uniformly distributed throughout the cross-section.

The effect of using a pole-piece instead of a coil for saturating the tape has been examined, using the method previously described to obtain the remanence curves shown in Fig. 8. These indicate the comparative effects of (A) A coil wound round the tape; (B) The same coil wound round a stalloy pole-piece with a flat tip; (C) The same coil wound round a pole-piece of which the thickness of the tip was reduced to about one-sixth of the total thickness.

It will be noticed that in curve C the slope is considerably reduced at the higher values of current. This is probably due to the effects of saturation at the tip of the pole-piece.

The situation will be somewhat more complex when a two-pole head is used. It was thought at one time that whenever two pole-pieces of opposite polarity were used for wiping or recording, as shown at the top of Fig. 9, the direction of magnetization of the tape leaving the heads was that of the magnetic flux between the two pole-pieces. It was assumed that since the stray flux on the running-off side of the heads must be lower in value than the flux between the pole-pieces, the former had little effect upon the final magnetic state of the tape. This, however, is only the case for a very small longitudinal gap between the pole-pieces.

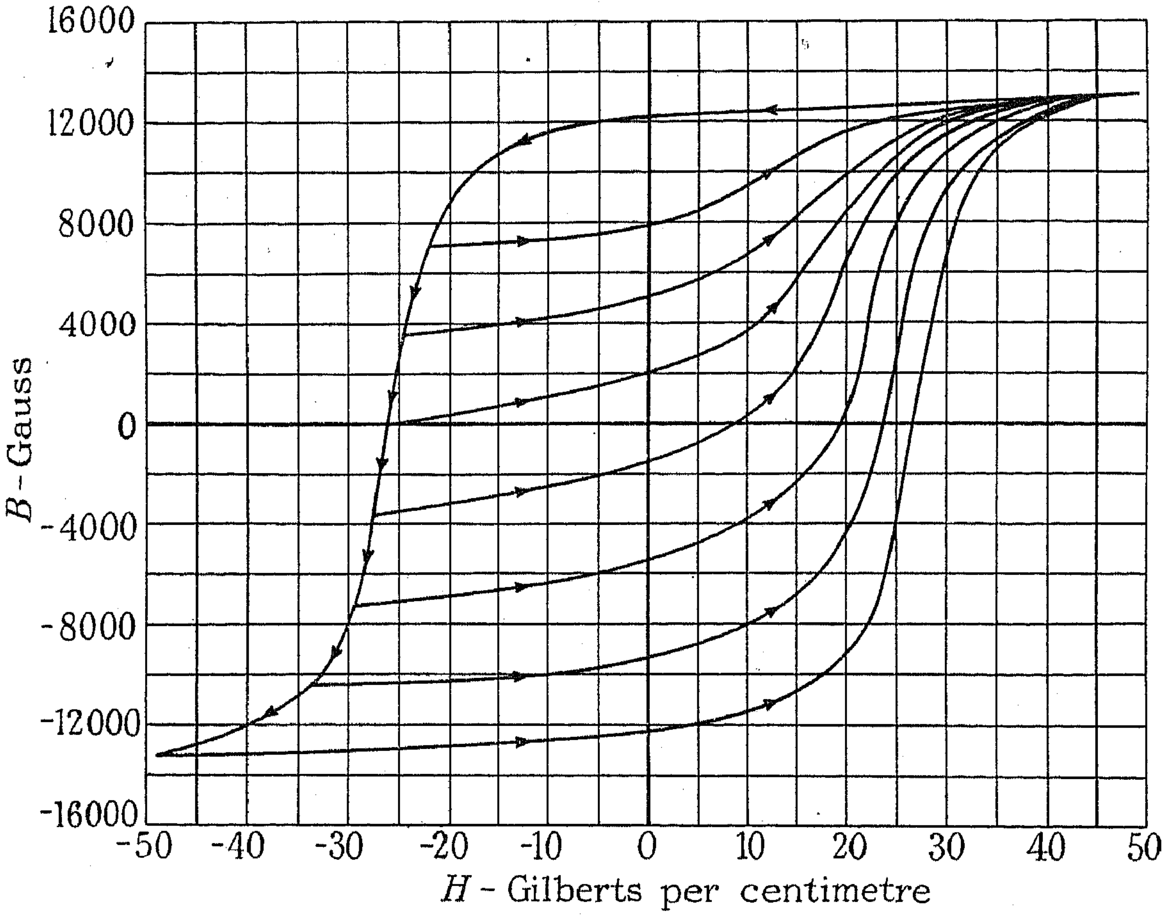

Fig. 6.—(B — H) characteristic for ring of tape.

Consider the case of a tape which has been fully magnetized by a field h_1 and is then passed through a two-pole wiping head in which the pole-pieces are widely staggered and of opposite polarity. Fig. 9 also shows the directions of the various fields to which the tape is subjected. As it approaches the leading pole-piece (P_1) it is subjected to the stray field h_2; then, between the pole-pieces, to the field h_3; and finally, as it leaves the head, to the stray field h_4 from the lagging pole-piece (P_2).

A curve (A in Fig. 9) has been plotted showing the relation between the current in the head and the resulting change of remanent induction in the tape ($B_{r\,max.} - B_r$) for positive and negative values of current.

For positive values of current the direction of h_3 is the same as that of the original saturating field h_1. The effect of h_2 is always largely counteracted by that of the

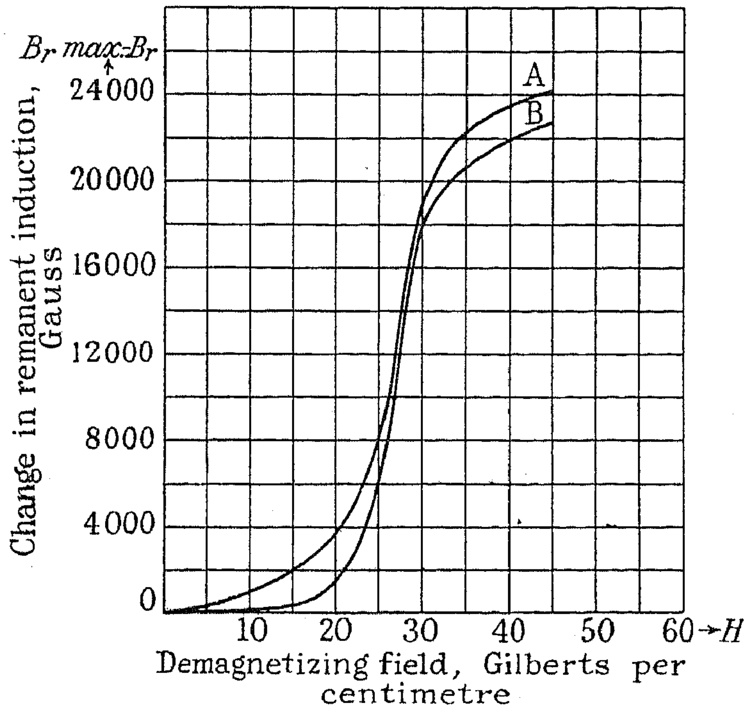

Fig. 7.—Comparison of remanence curves for ring and running tape.

A.—Ring of tape.
B.—Running tape.

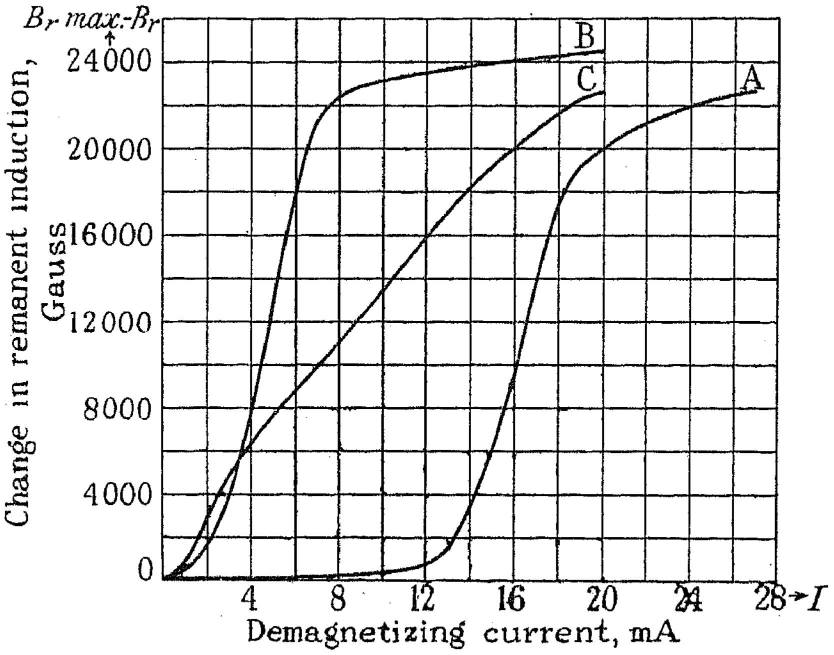

Fig. 8.—Comparison of remanence curves for coil and pole-pieces.

A.—Coil wound round tape.
B.—Same coil wound round saturating pole-piece on tape.
C.—Same coil wound round sharpened pole-piece on tape.

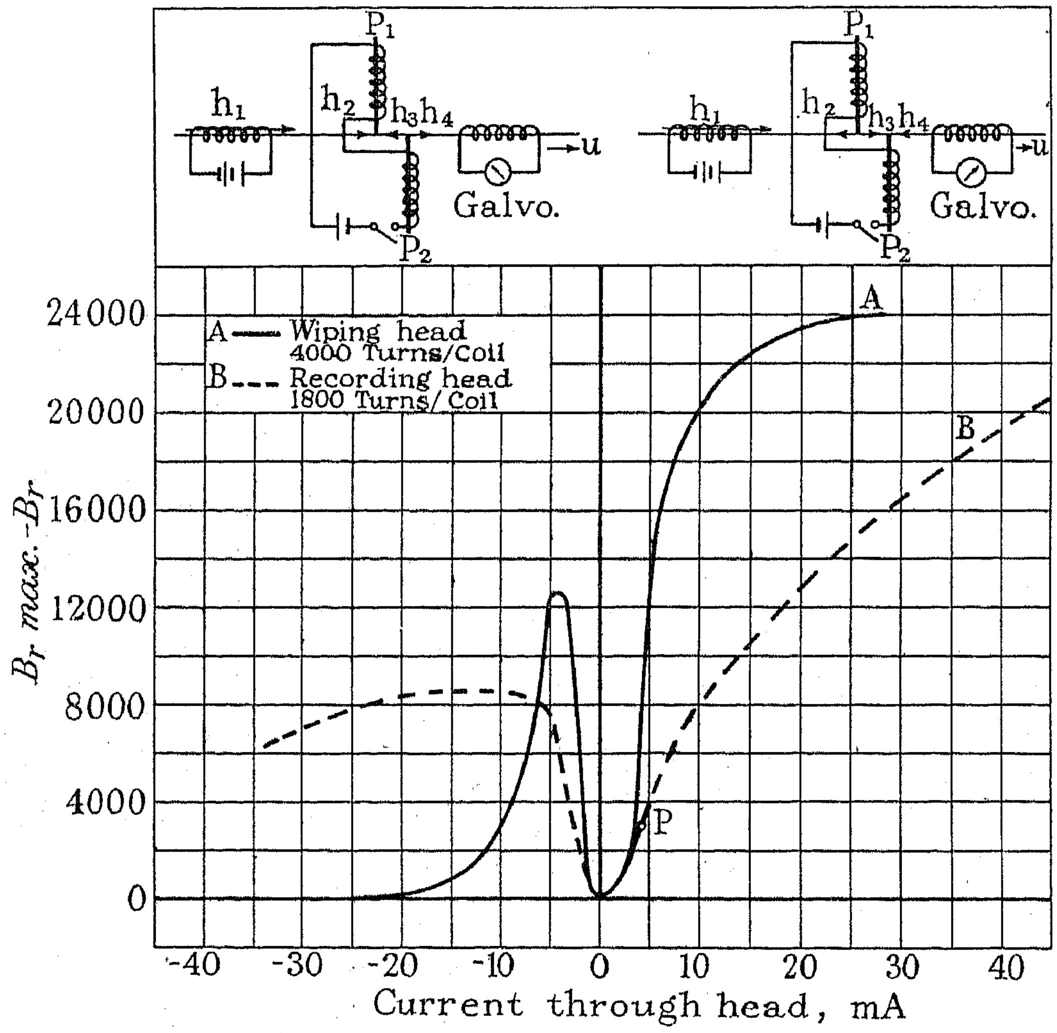

Fig. 9.—Remanence curves for two pole-pieces.

stronger field h_3, and the main change of remanent induction is produced by h_4. A value of current is reached at which the tape leaves the head fully magnetized in the direction of the field h_4.

For negative values of current, the direction of h_3 is opposed to that of h_1, h_2, and h_4. As the field h_3 is considerably greater than h_4 the rate of change of remanent flux with current is at first greater, and the curve rises more sharply, than in the previous case when h_4 was producing the change. A point is reached, however, when the tape tends to become saturated by h_3, so that further increases of current have less and less effect upon its state between the pole-pieces. The effect of h_4, however, still increases with an increase of current, and the curve bends over and returns gradually to the zero line as h_4 eventually becomes great enough to saturate the tape in the original direction. It is thus seen that, provided the saturating current is large enough, the final direction of magnetization of the tape is determined by the direction of the field h_4 and not by that of h_3.

A similar argument applies to the performance of a two-pole recording head with sharpened pole-pieces widely staggered. The curve for this head is shown as B in Fig. 9. From this it may be seen that when h_4 is in the same direction as h_1 the curve for a wiping head (A in Fig. 9) bends over and approaches the datum line, but with a recording head (B in Fig. 9) this tendency is very much reduced. The number of turns on each coil is 4 000 in the case of the wiping head and 1 800 in the case of the recording head. Apart from this, the difference in the behaviour of the two heads is probably due to saturation effects in the sharpened tips of the recording pole-pieces.

In practice, when using this double-pole system the value of demagnetizing current is such that when the a.c. recording current is zero the state of the tape leaving the recording head is represented by point P (Fig. 9).

The foregoing remarks immediately indicate the possibilities of various other arrangements of wiping and recording heads, including the use of one instead of two pole-pieces. A number of these arrangements have been tried with varying degrees of success, and will now be considered.

Wiping Systems

The purpose of the wiping head is to remove all previous flux variations in the tape, and to ensure that it is fully and uniformly magnetized in a longitudinal direction when it approaches the recording head.

Three alternative wiping systems are shown in Fig. 10.

(*a*) *Coil.*

In the centre of the coil the field will be almost entirely longitudinal, and the tape should be entirely saturated, provided that the field strength is adequate. In practice this method is not readily applicable, owing to the fact that the tape must be threaded through the coil.

(*b*) *Single pole.*

The distribution of the field from a single pole in contact with the tape is such that the tape is saturated in one direction as it approaches the pole-piece and in the opposite direction as it leaves it.

(*c*) *Two poles with a gap between them in the direction of the motion of the tape.*

In this case the tape experiences a further reversal in the direction of its longitudinal magnetization.

Both the single- and the two-pole systems can be made to give satisfactory results.

Recording Systems

A number of alternative arrangements and methods of excitation of pole-pieces are shown in Fig. 11, to which reference is made in the following description of their operation. These are grouped under three headings:—

(1) Single pole.
(2) Two poles with a wide gap between them.
(3) Two poles with a narrow gap between them.

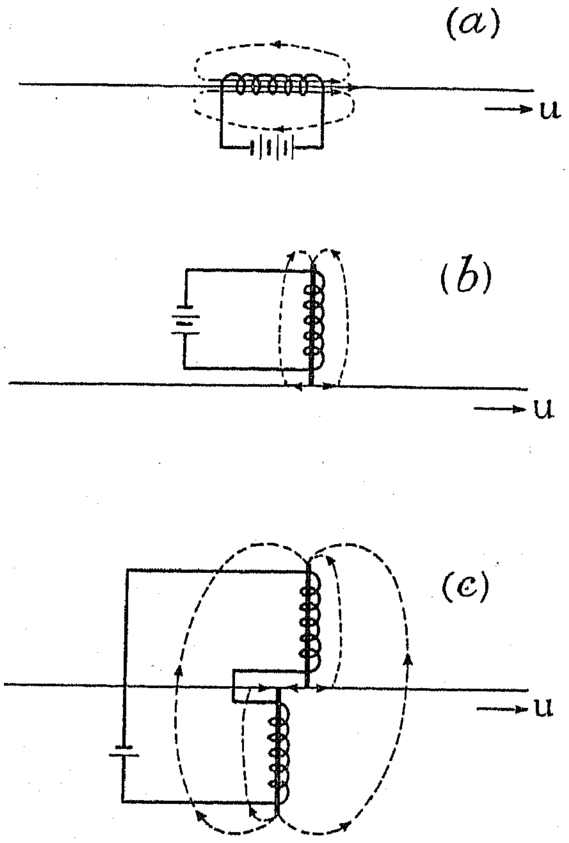

Fig. 10.—Wiping systems.
(*a*) Coil.
(*b*) Single-pole.
(*c*) Two-pole.

In group (1) the recording is carried out by the demagnetizing field on the trailing side of the pole-piece.

In group (2) it is largely carried out by the field on the trailing side of the second pole-piece.

In group (3) it is largely carried out by the main field between the pole-pieces.

The exact nature of the field distribution with any given arrangement is uncertain, but it would seem probable that in groups (1) and (2) the recording field rises sharply to a maximum near the trailing edge of the trailing pole-piece and then falls off rapidly. With a narrow gap, as used in group (3), the field distribution is much more nearly square-topped.

In the case of group (3), with the exception of system No. (3*a*), any lengths of tape demagnetized by the main recording flux between the pole-pieces are subsequently subjected to the stray field on the trailing side of the second pole-piece, which is, of course, in the opposite direction. If the pole-pieces are accurately ground and adjusted, however, this stray field should be exceedingly small when the gap is very narrow, but otherwise it may well become appreciable.

***Group* (1).**

The simplest recording head consists of a single pole with a single magnetizing winding in which the alternating current is superimposed upon the direct current. If wiping is carried out with a single north pole, the recording pole must be a south pole, and vice versa. As the tape approaches the recording pole-piece it is subjected to the field h_3 which is in the same direction as the saturating field h_1, so that when it reaches the centre of the pole-piece, where the longitudinal field is zero, the tape will still have approximately its maximum possible remanent longitudinal magnetization. As it moves away from the pole-piece it is subjected to h_4, which is in the demagnetizing direction and carries out the recording.

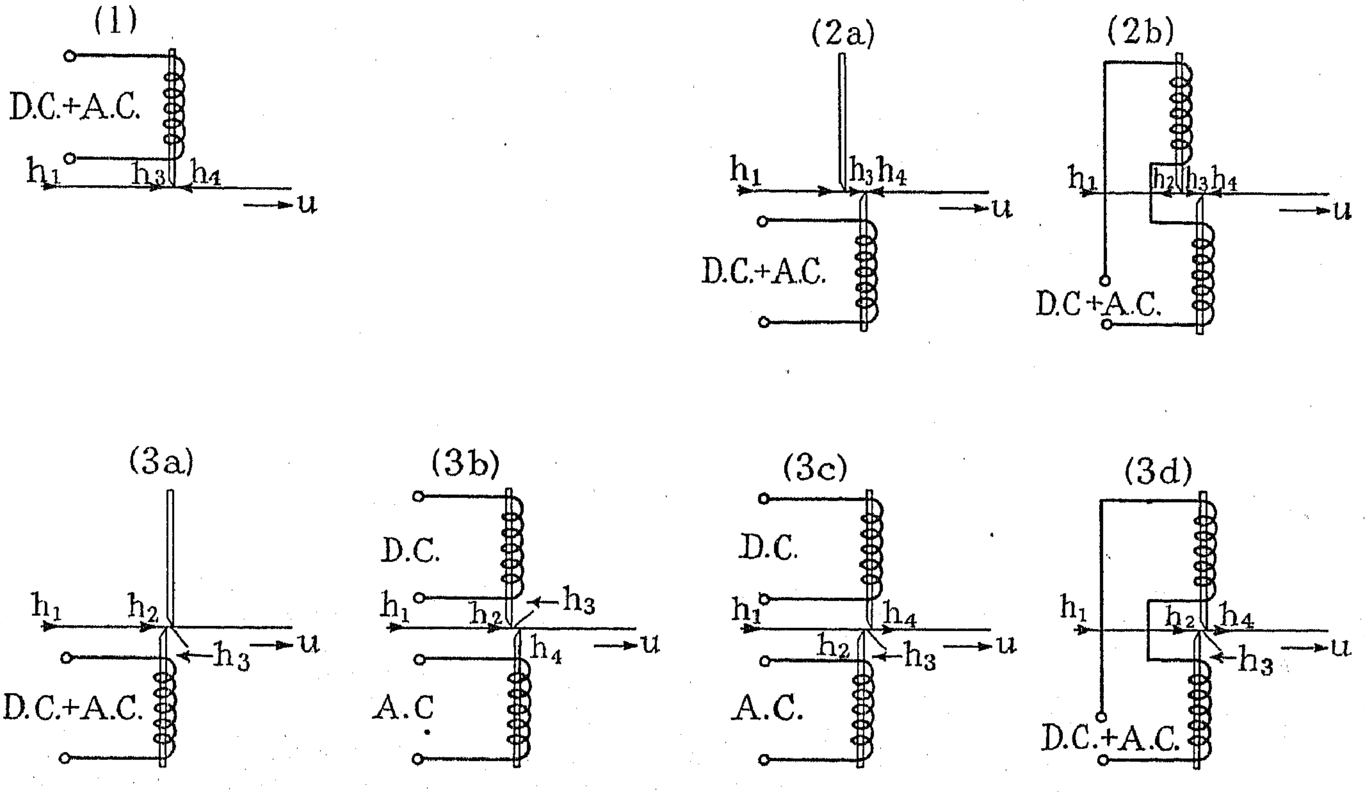

Fig. 11.—Recording systems.

***Group* (2).**

With both these arrangements the exact setting of the longitudinal gap between the pole-pieces is not of fundamental importance, and about 3 mm. appears to give the best results. The function of the first pole-piece is not very clear, but results appear to be improved by its presence. In all probability it serves mainly to reduce the spread of the recording field h_4.

In case (*a*) the operation is almost identical with that of the single pole-piece of group (1).

In case (*b*), which is known as the " D.P." system, the tape approaching the first pole-piece is demagnetized by h_2, but as it passes under the pole-piece it is subjected to h_3, which is in the saturating direction. The distribution of this field is such that it is at a maximum under the trailing edge of the first pole-piece and under the leading edge of the second pole-piece, while in between it may be slightly lower. Since the thickness of the pole-piece is small compared with the shortest wavelength to be recorded, the value of the alternating components of h_2 and h_3 will not have appreciably changed as the tape passes under the first pole-piece, and the demagnetization due to h_2 is counterbalanced by the saturation due to h_3. Recording is then carried out by the second pole-piece in much the same manner as with a single pole-piece.

With the arrangement of group (2) it seems that slightly better results are possible at the higher frequencies than with group (1), but at lower frequencies the converse holds.

***Group* (3).**

(*a*) This system has been termed the single-pole and idle-pole, or " S.P.I." system. The second pole-piece is unexcited and therefore does not produce any net reversed stray field, but serves to concentrate the recording field h_3.

(*b*) and (*c*) The advantage of these two systems is that the d.c. and a.c. components of demagnetizing current are separated, so that there will be a reduction in the asymmetrical distortion of the waveform due to the saturation of the tip of the a.c. energized pole-piece.

In (3*b*) the final stray field to which the recorded tape is subjected is alternating, while in (3*c*) it is approximately constant in magnitude and direction. On the other hand, considering the effect of the stray field h_2 as the tape enters the head, in the case of (3*b*) this will be constant and in the same direction as the original saturating field h_1, so that the recording is carried out upon tape that is always in the same magnetic state. In (3*c*) h_2 is alternating, and this condition does not apply, although in any case the stray fields should be very low.

(3*d*). In this arrangement the method of excitation is similar to that of (2) (*b*) but has reversed polarity.

The tape recorded by h_3 is subjected to the field h_4 which has both d.c. and a.c. components, each of which is liable to be lower than the corresponding component in (3*b*) and (3*c*).

In group (3) the adjustment of the head is very critical and the procedure in each case is to set the poles opposite to one another and then to increase the longitudinal gap between them until the output from the reproducing head at 6 000 cycles is a maximum.

The variation in the results obtained with the four arrangements of group (3) is not very great. It would appear, however, that with all of them a higher level may be recorded than with either group (1) or group (2), but that under practical conditions distortion at low levels is liable to be slightly worse.

Reproducing Systems

Three types of reproducing systems are mentioned and are illustrated in Fig. 12.

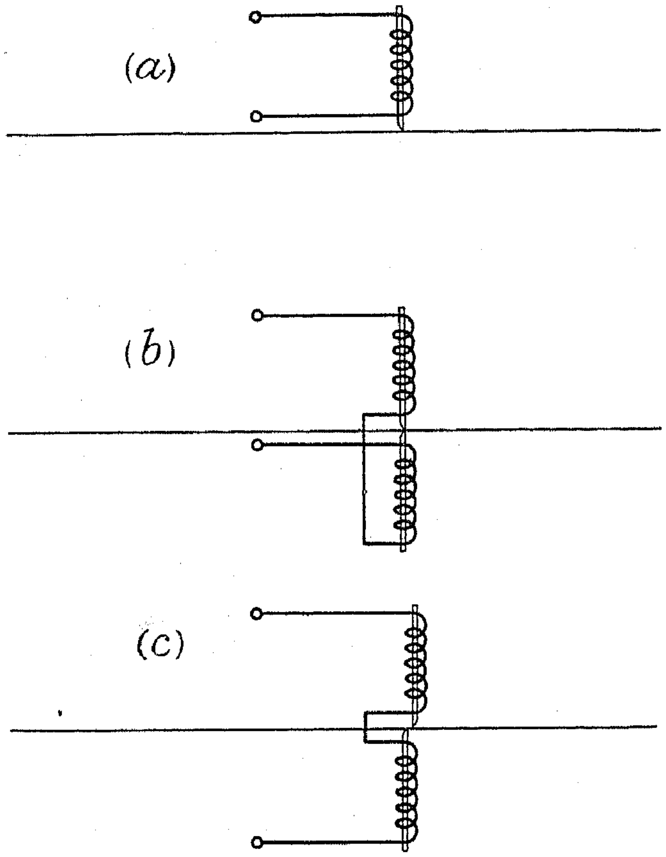

Fig. 12.—Reproducing systems.

(i) *Single pole-piece.*

The operation of this has already been briefly described in Section (1). This system has the very great advantage that extremely consistent results may be obtained, since no adjustments have to be made.

(ii) *Two pole-pieces opposite each other.*

The operation of this system is, in theory, almost identical with that of a single pole-piece. The coils round the pole-pieces are connected in series opposing, so that the e.m.f.'s generated are additive. It would appear from practical experience that the presence of pole-pieces on either side of the tape results in a higher efficiency of pick-up at high frequencies than is the case with a single pole-piece. The system has the disadvantage that the pole-pieces must be very accurately set or consistent results will not be obtained.

(iii) *Two pole-pieces with a gap between them.*

In this case the coils are connected in series aiding. The net e.m.f. induced in the two coils is proportional to the difference between the rates of change of the number of flux-turns in each coil. This difference will be a maximum when the distance between the pole-pieces is adjusted to be equal to one-half of the wave-length of the flux alternations in the tape. Although this system was used for some time, it is very difficult to adjust the distance between the pole-pieces very accurately, so that a consistently uniform frequency characteristic is not always obtained from the system.

In addition to the simple forms of heads that have been described above, there are a large number of other possibilities. These include ring-type heads, which consist of a ring-shaped core carrying a single winding and having a small gap in the centre of the portion in contact with the tape. The plane in which the ring lies is parallel to the length and thickness of the tape. This type of head has been developed in Germany in connection with the use of magnetic dust-coated film instead of steel tape.

After experimental work in this country with different types of heads, two recording systems, known as the "D.P." and "S.P.I." (2*b* and 3*a*, Fig. 11) have emerged; these are used by the British Broadcasting Corporation and the Marconi Co. respectively. It is fully realized that both these systems are subject to serious disadvantages from both a theoretical and practical point of view, but at the time of writing the authors have found no other system giving more satisfactory results under service conditions.

In each case a single-pole-piece reproducing head is used.

The Complete Recording Chain

Individual systems of wiping, recording, and reproducing, have already been discussed. The problem of obtaining the best results from the complete recording and reproducing chain for any given arrangement of the various heads involves the question of the adjustment of the recording head, and the working point on the $(B - H)$ curve, as well as the best possible recording frequency characteristic and the corresponding reproducing frequency characteristic.

It has already been pointed out that the total volume range of any system of recording is bounded on the one hand by amplitude non-linearity and on the other hand by considerations of background noise. To a certain extent the frequency range will also be bounded by the same two factors. For although, within limits, it is possible to apply frequency correction circuits to the reproducing amplifier which will give a frequency characteristic that is substantially flat over a very wide range, in so doing the signal/noise ratio may be reduced.

The frequency characteristic of the recording amplifier should be chosen to allow the recording level to be as high as possible for a given amount of distortion under all programme conditions, so that the maximum signal/noise ratio is obtained. This condition involves not only the characteristics of the recording chain but also the energy distribution of the programmes to be recorded, which will be very varied. Numerous experiments have been carried out in this connection, and it is generally accepted that the maximum energy in the frequency spectrum of speech and music occurs in the neighbourhood of 300 cycles per sec.

Curve A of Fig. 13 shows the variation with frequency of the peak energy levels occurring in a typical orchestral programme as determined by Harvey Fletcher,* and curve B shows the maximum level, consistent with linearity, which may be applied to the input of the recording amplifier for any single frequency, deduced from the results of experiments on the D.P. system. It must be noted, however, that this curve does not show the modulation effects of one frequency upon another, as will be explained later.

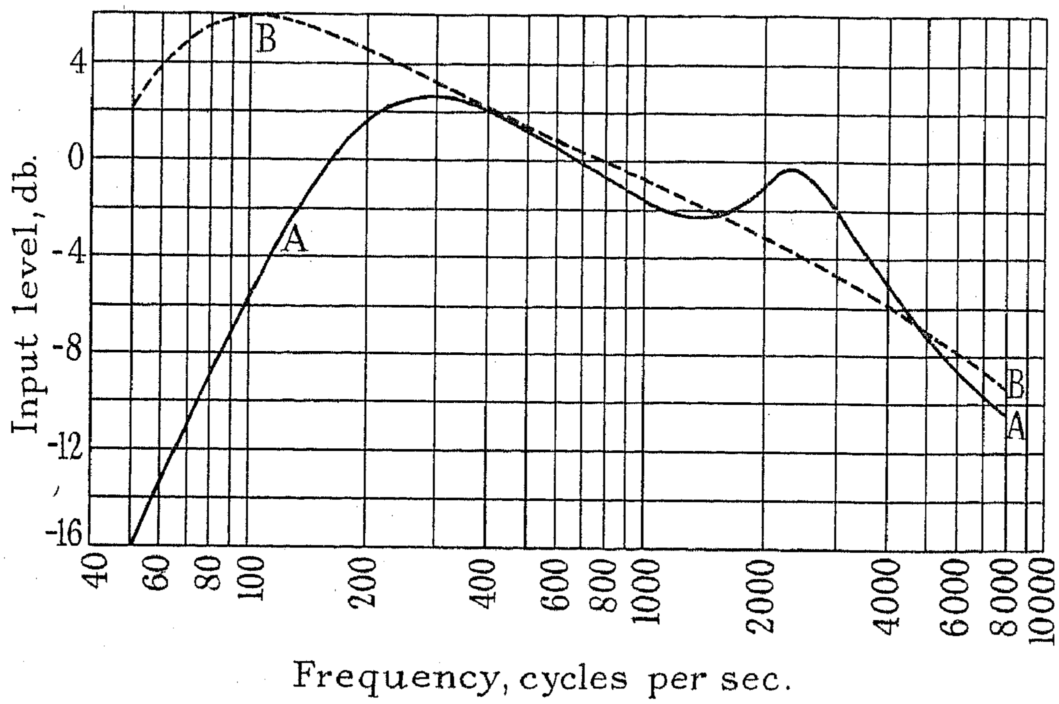

Fig. 13.—Peak energy levels occurring in orchestral programme.

In carrying out comparative tests upon recording heads, measurements of the reproduced signal must be made, since a satisfactory direct method of measuring the magnetic state of the tape has not been developed. The frequency discrimination of the reproducing system must be taken into account, however, when measuring the relative levels of different frequencies reproduced, but this is, of course, dependent upon the recording characteristic if the overall frequency response is to be flat. To avoid this complication a form of test is often required which involves a single frequency only. In this connection the linearity curve has proved most useful. If the input level to the recording head is plotted against the output level from the reproducing head to the same scale, the resultant curve should be a straight line at 45° to either axis. Departure from this line in either direction indicates amplitude non-linearity which would give rise to distortion. With this system of recording it is usual for the reproduced level to rise sensibly linearly with the recording level up to a point beyond which it falls below the linear value. Eventually a maximum reproduced level is reached such that further increases of recording level produce a reduction in the reproduced level.

These linearity curves can be used first of all to determine the most suitable working point on the $(B - H)$ curve, as well as the best adjustment of the recording head. An examination upon a cathode-ray oscillograph of the changes in the reproduced waveform while making these adjustments is often of great value.

The authors have found, however, that the results of listening tests when recording programmes do not always agree with the results of tests using single frequencies. In fact, a single-tone test is inadequate to determine the distortion of the particular system under consideration, and experiments using two tones should be made. This statement may be made clearer by citing an example. In Fig. 14 input/output linearity curves are shown for three frequencies with different values of demagnetizing current, using the D.P. recording system. It will be seen that the output level is dependent upon the value of this current throughout the straight and useful portion of the curves. Bearing in mind the process of recording described earlier in the paper, imagine that two tones having frequencies of, say, 100 and 4 000 cycles per sec. are being recorded simultaneously. The variation in the value of the recording current due to the low frequency effectively alters the mean value of the demagnetizing current upon which the high-frequency alternations are superimposed. This tone is thus modulated during the recording process at 100 cycles per sec., which produces a type of distortion that is not directly shown up by experiments using a single tone.

The recording characteristic used in practice will also depend, to a certain extent, upon the method used for monitoring the input level to the recording amplifier. Since it is possible to listen to the reproduced signal a fraction of a second after recording, it is usually convenient to make use of this facility to determine the highest permissible recording level for control purposes. In order to do this, overloading must occur before suitable adjustment can be made. It has been found that with aural control the quality of the reproduction, as a whole, suffers least if overloading is first apparent at the lower frequencies, rather than simultaneously throughout the frequency range. Under these circumstances the recording characteristic may be modified at the lower frequencies to produce this effect.

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* "Some Physical Characteristics of Speech and Music," *Bell System Technical Journal*, 1931, vol. 10, p. 349.

The frequency characteristic of the reproducing amplifier must be adjusted to give an overall frequency response that is sensibly flat throughout the required range, while maintaining a satisfactory signal/noise ratio.

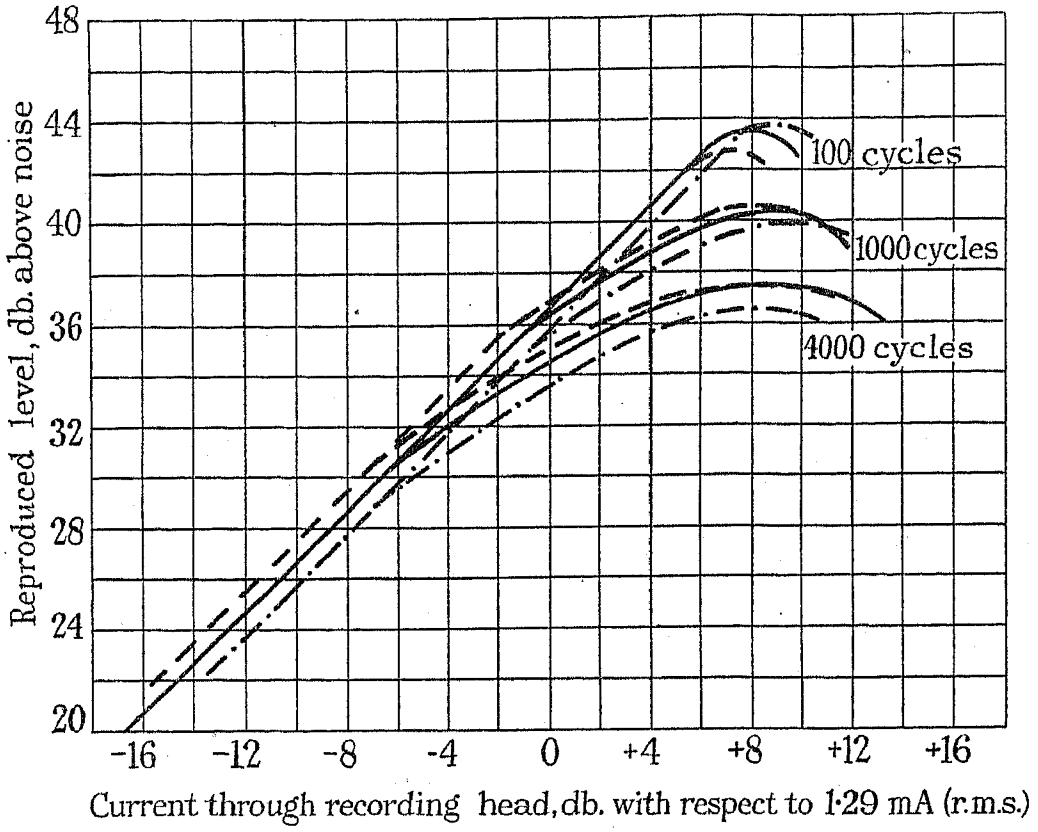

Fig. 14.—Input-output linearity curves for D.P. system.

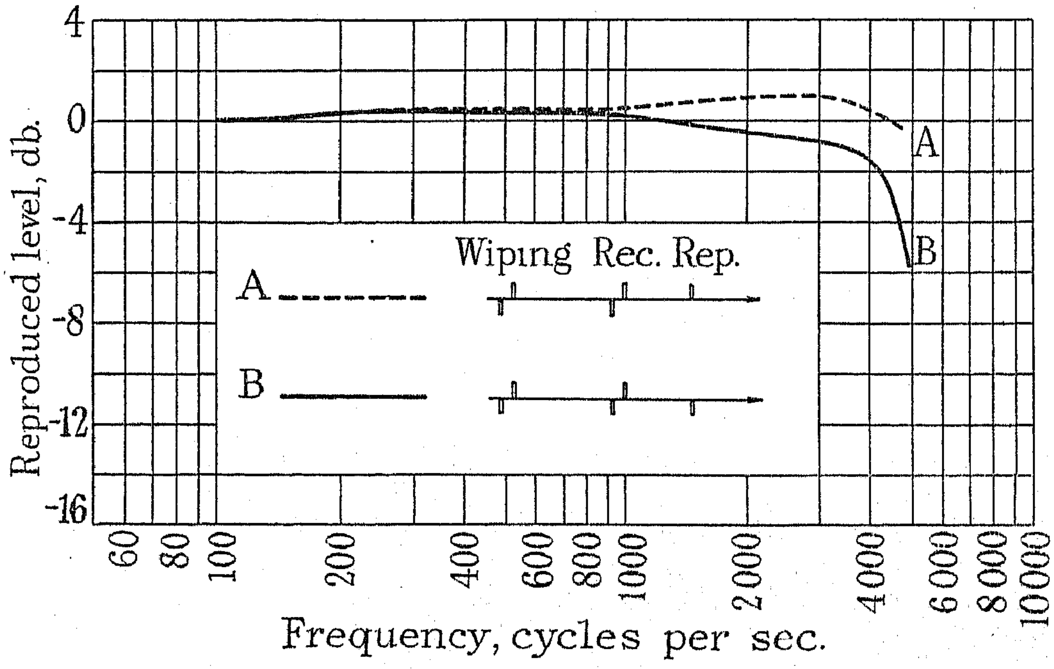

Fig. 15.—Effect of asymmetrical recorded flux distribution.

When the reproducing frequency characteristic is such that the reproduced noise is most noticeable at the higher frequencies, it is sometimes found that by attenuating all frequencies above, say, 5 000 cycles per sec., the improvement in the signal/noise ratio more than compensates for the reduction of frequency range. This has actually been done in the case of the D.P. reproducing amplifier, of which the frequency/response characteristic is given in Fig. 16.

Various quantitative measurements may be carried out upon the complete recording and reproducing chain, of which the most instructive are probably the input/output linearity curves, and two tone tests for a high and a low frequency. It is thought that the more usual harmonic tests are of secondary importance, since their main object is to show up non-linearity which will result in the production of intermodulation tones.

The ultimate test of any recording system, however, is to listen to the reproduction of a number of recorded programmes and to compare them with the direct programmes under identical listening conditions.

Some of the details and some of the results of tests upon the D.P. and S.P.I. systems now in use are given below.

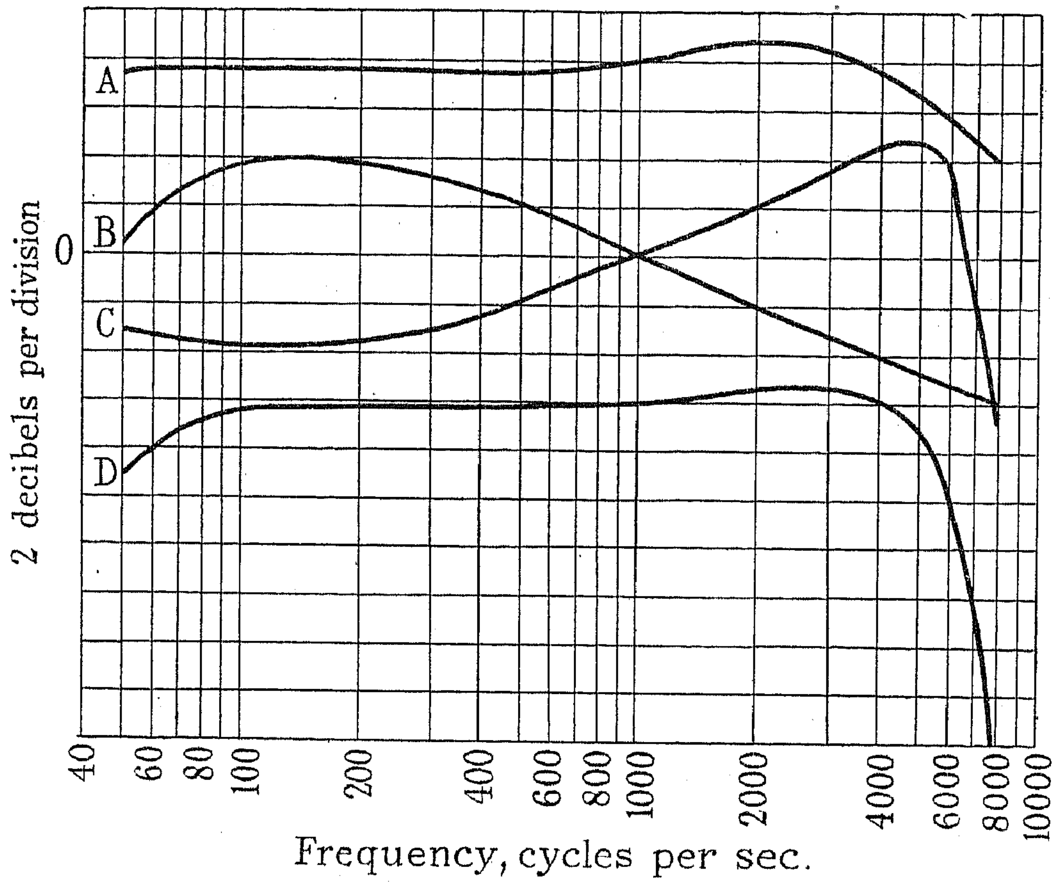

Fig. 16.—Frequency/response characteristic for D.P. system.

The D.P. and S.P.I. Systems of Recording.

These two systems are illustrated in Figs. 11, 2*b* and 3*a*, and a brief explanation has already been given of their operation. In practice they are both used with a single-pole reproducing system. The reproducing pole-piece runs on the same side of the tape as the lagging recording pole-piece in the D.P. system, and the energized pole-piece in the S.P.I. system. The effect of placing the reproducing pole-piece on the other side of the tape is shown in Fig. 15. Curve A shows the overall frequency/response characteristic of the D.P. system taken with the reproducing pole-piece on the same side of the tape as the lagging pole-piece in the recording head. Curve B shows an equivalent curve, the reproducing pole-piece being on the opposite side of the tape. It will be seen that there is a considerable loss at the high frequencies in the latter case, but that the reproduced level at the lower frequencies is the same. This suggests that where the wavelength is great compared with the thickness of the tape the external flux distribution is symmetrical on either side, but that where the wavelength is comparable with the thickness the density is greater on the side of the tape that carries the lagging pole-piece. Therefore, in practice, the reproducing pole-piece is always used on this side.

It has been found that a slight improvement in results is obtained when the recording and reproducing pole-pieces are reduced at the tips in width as well as in thickness, so that the whole of the width of the tape is not uniformly demagnetized by the recording head.

Stalloy is used for recording, and permalloy for reproducing, pole-pieces, which are stamped from 0·015-in. sheet (i.e. 0·37 mm.) and are 3 mm. wide and 19 mm. long. The tips are reduced in width to 2 mm., and in thickness, i.e. in the direction of motion of the tape, to 0·06 mm. They are, of course, heat-treated after shaping. The best value for the demagnetizing current has been found to be 4 mA for the D.P. system and 3 mA for the S.P.I.

The frequency/response characteristics of the two systems are shown in Figs. 16 and 17. In each case the four curves refer to the current in the recording heads (A), the magnetic systems which include the recording heads, the tape and the reproducing heads (B), the reproducing amplifiers (C), and the overall chains (D), and are drawn one below the other at entirely arbitrary intervals.

Measured under these conditions, input/output linearity curves for the D.P. system have already been given in Fig. 14, while Fig. 18 shows the results of two tone tests using 105 cycles and 4 000 cycles per sec., Curves A′, B′ and C′ show the root-sum-squared level of the intermodulation tones [r.s.s. (4 000 ± 105*n*)] for varying output of the low-frequency tone corresponding to levels of the high-frequency tone given by curves A, B, and C, respectively. It appears that the r.s.s. level of the intermodulation tones is proportional to the reproduced level of both the recording tones. With the S.P.I. system results of the same order are obtained, but the distortion is in general lower for very high levels of the higher frequency and higher for very low levels. In this case it is definitely advantageous to record with a recording frequency characteristic that rises at the higher frequencies, as may be seen in Fig. 17.

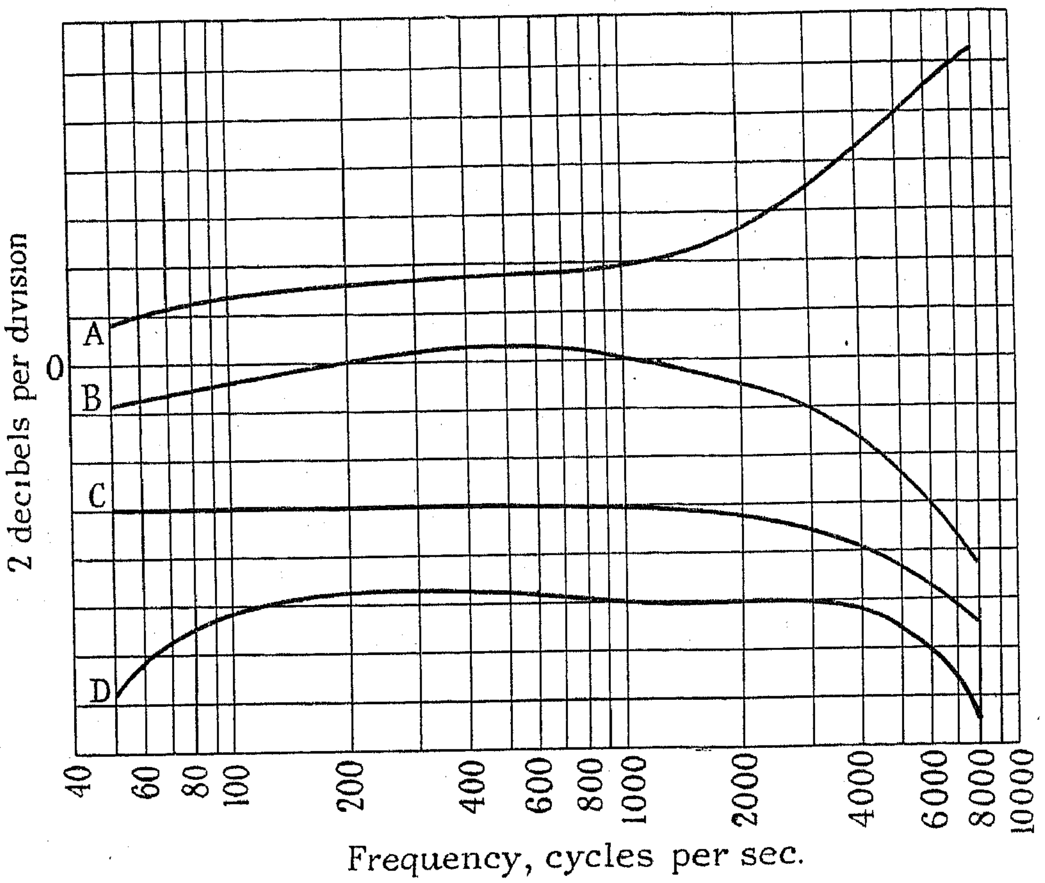

Fig. 17.—Frequency/response characteristics for S.P.I. system.

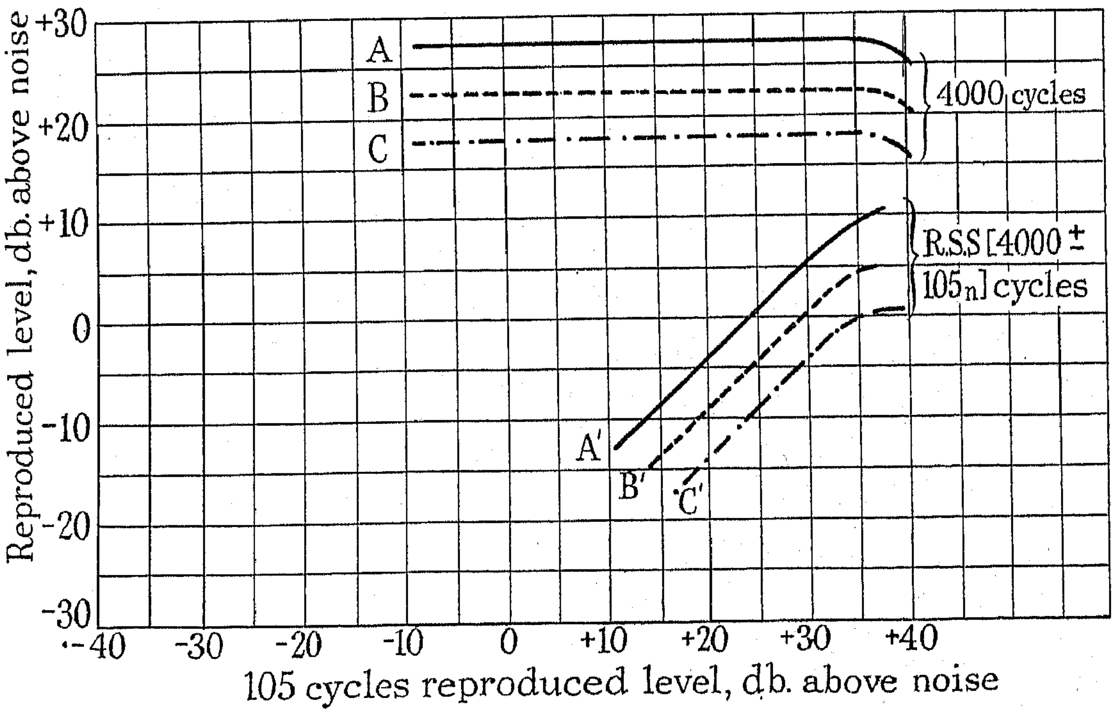

Fig. 18.—Levels of intermodulation tones reproduced when a tone of 105 cycles per sec. is recorded together with a constant level of 4 000-cycle tone on the D.P. recording system.

A.—Recording tone of 4 000-cycle tone:— 9 db./1·29 mA.
B.—Recording tone of 4 000-cycle tone:—14 db./1·29 mA.
C.—Recording tone of 4 000-cycle tone:—19 db./1·29 mA.

Measurements of the signal/noise ratios obtainable in practice with the two systems give figures ranging from 35 to 45 db.

In spite of the fact that from test-results on tone it would appear that a greater amplitude range can be obtained with the S.P.I. than with the D.P. system, it is found that under practical conditions there is very little to choose between them, and both systems are in use at the present moment.

Plate 1

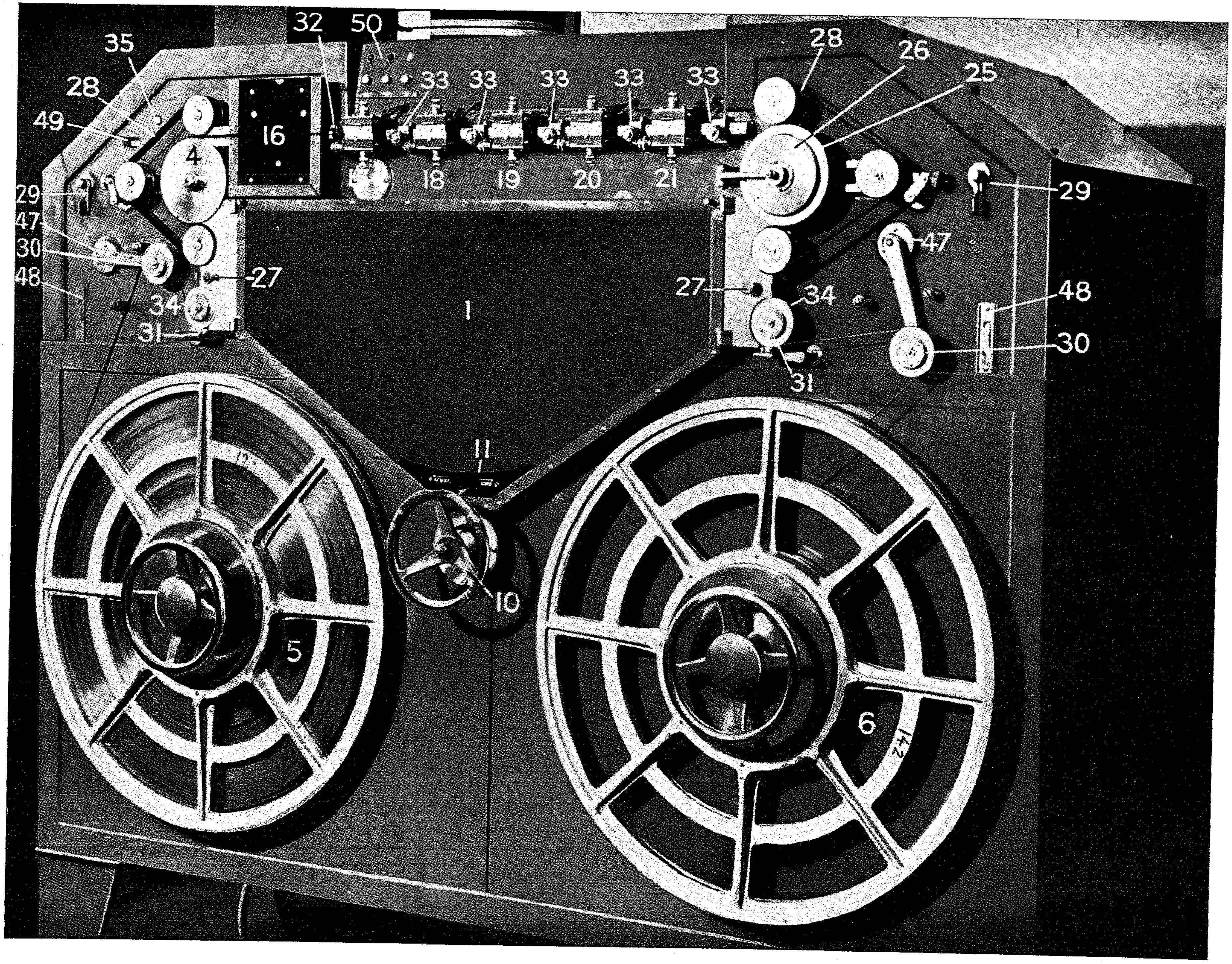

Fig. 19.—Front view of machine.

1. No. 1 tape reservoir.
4. No. 2 tape-drive wheel.
5. Left-hand tape reel.
6. Right-hand tape reel.
10. Starting handle.
11. Contact, No. 1 reservoir.
16. No. 2 tape reservoir.
17. Wiping head.
18 and 19. Recording heads.
20 and 21. Reproducing heads.
25. Tape drive wheel.
26. Tape drive wheel clutch.
27. No. 1 tape reservoir entry door.
28. Tape drive belt.
29. Quick-release toggle.
30. Spring jockey pulley.
31. Tape tension brake.
32. Friction pad.
33. Tape guide.
34. Lower guide wheel.
35. Pilot light.
47. Tape jockey-arm bearing.
48. Tape tension brake adjustment.
49. Tape travel indicator.
50. Cue lights.

Plate 2

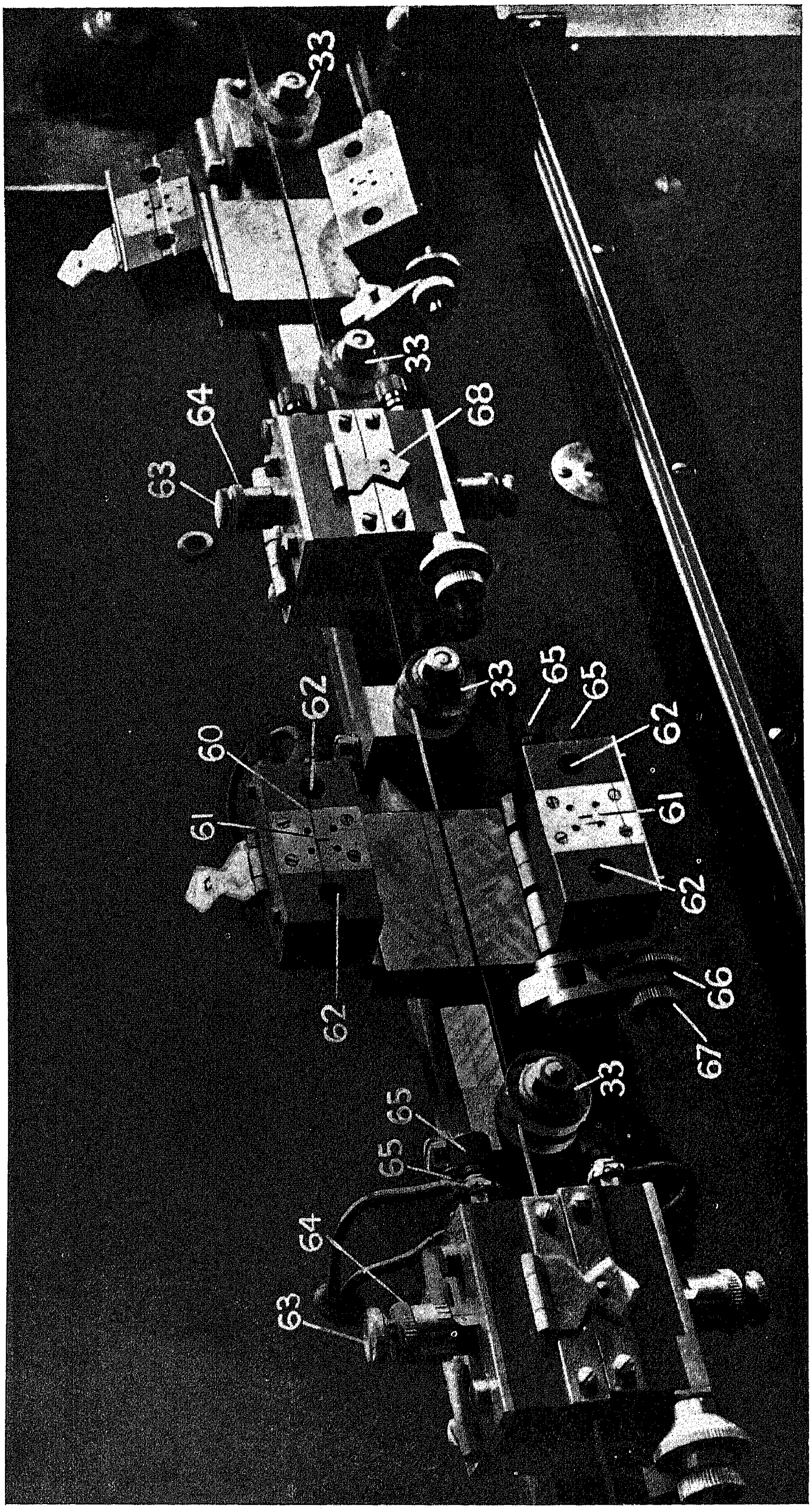

Fig. 20.—Recording and reproducing heads.

33. Tape guide.
60. Tape groove.
61. Slot for pole-piece.
62. Felt pad.
63. Pressure pin.
64. Spring-tension adjuster.
65. Terminals.
66. "Stagger" adjusting screw.
67. Lock nut.
68. Clamp.

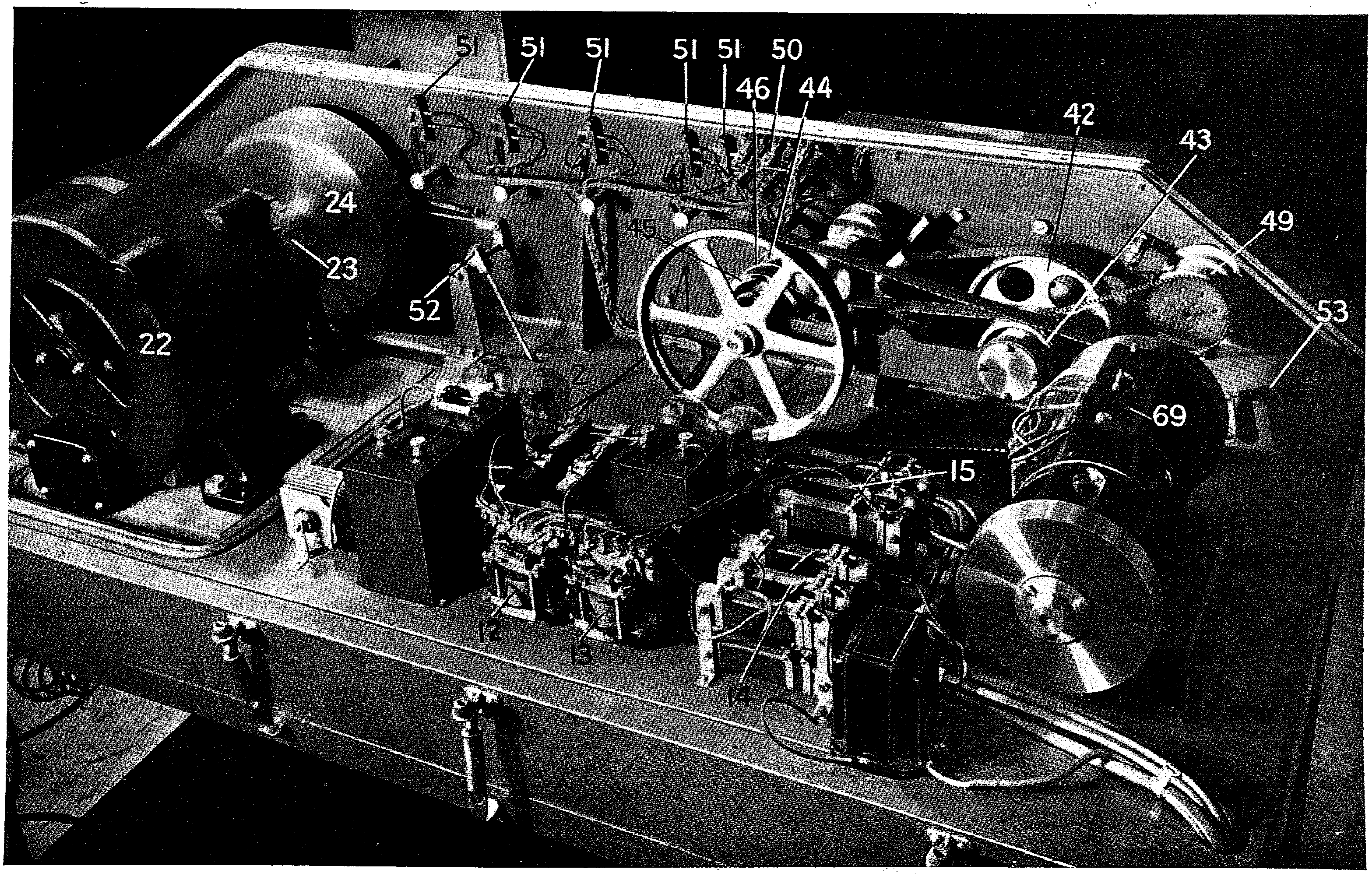

Fig. 21.—Back view. Upper deck (covers removed).

2. Thyratrons (No. 1 System).
3. Thyratrons (No. 2 System).
12. Relay, No. 1 System.
13. Relay, No. 2 System.
14. No. 1 motor resistances.
15. No. 2 motor resistances.
22. No. 3 motor (constant feed).
23. Flexible coupling.
24. Oil-damped flywheel.
42. Forward-driven pulley (No. 2 tape drive wheel).
43. Backward-driven pulley (No. 2 tape drive wheel).
44. Forward driving pulley (No. 2 tape drive wheel).
45. Backward driving pulley (No. 2 tape drive wheel).
46. No. 2 automatic dog clutch.
49. Tape travel indicator.
50. Cue lights.
51. Head connection blocks.
52. Tape drive wheel clutch-operating mechanism.
53. Quick-release toggle adjustment.
69. No. 2 motor.

Plate 4

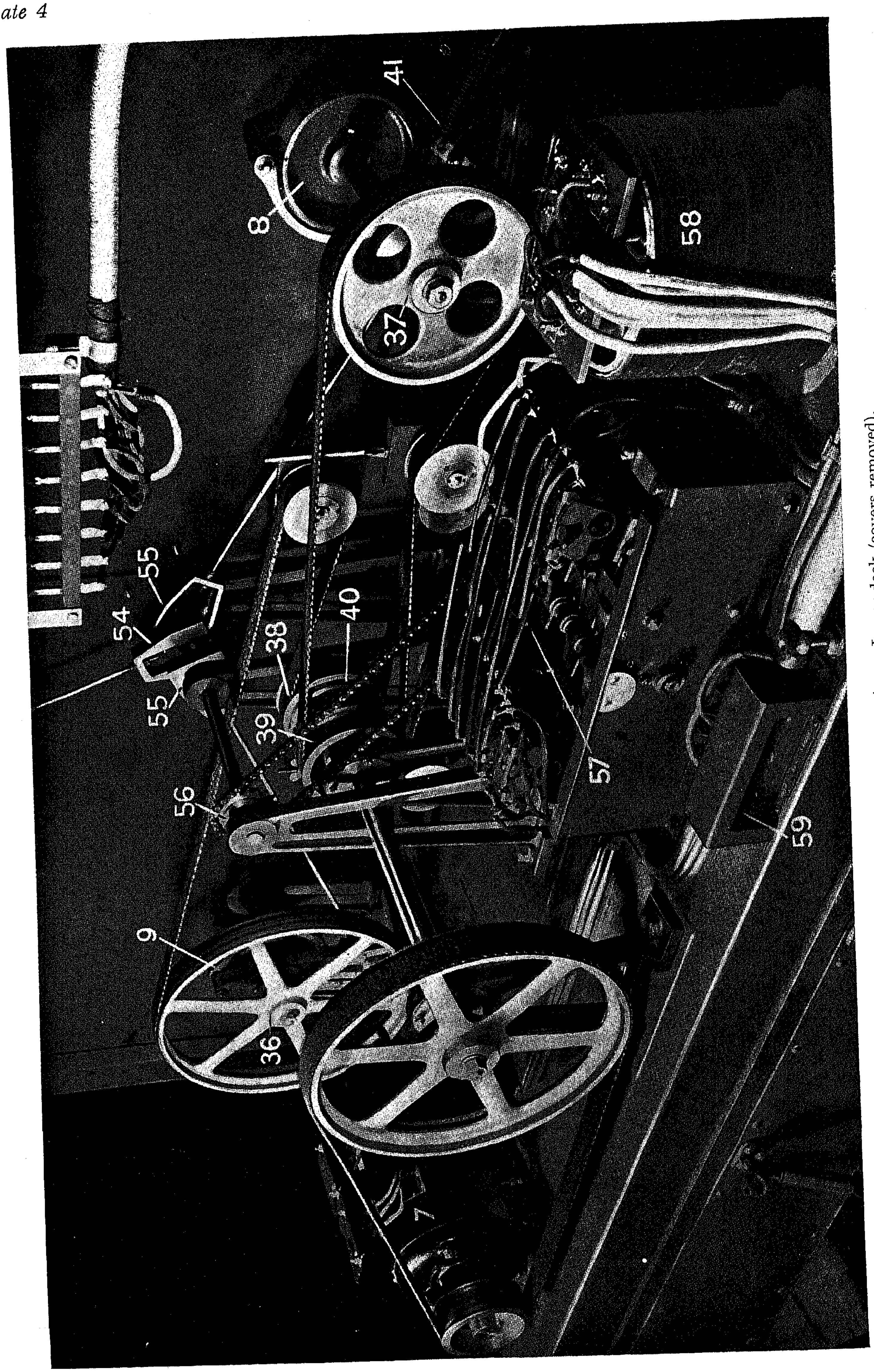

Fig. 22.—Back view. Lower deck (covers removed).

7. No. 1 motor (winding).
8. Brake, left-hand tape reel.
9. Brake, right-hand tape reel.
36. Right-hand tape reel driven pulley (forward).
37. Left-hand tape reel driven pulley (rewind).
38. Right-hand reel driving pulley (forward).
39. Left-hand tape reel driving pulley (rewind).
40. No. 1 automatic dog clutch.
41. Brake springs.
54. Cam-operated mechanism for tape drive wheel clutch.
55. Cam-operated mechanism for brakes.
56. Operating mechanism for "forward-reverse" switchgear.
57. "Forward-reverse" switchgear.
58. Power transformer (thyratron circuits).
59. Main 3-phase connection block.

SECTION (3)

The Tape

The results of the recording system as a whole are to a great extent dependent upon the quality and uniformity of the steel tape.

A tungsten magnet steel is used, having the essential properties of high coercivity and remanence. It is melted in an acid open-hearth furnace from pig-iron produced in an electric charcoal blast-furnace from the purest ores, and scrap iron of known analysis. It is first of all hot-rolled under temperature control and then cold-rolled, cut, and polished, undergoing various heat treatments during the process of such a nature that the possibility of magnetic ageing is reduced to a minimum. This allows a tape to be stored for a number of years after recording without noticeable deterioration of the quality of the recording. The final dimensions of the tape are 0·08 mm. thick and 3 mm. wide, and it is rolled into lengths of about 1 000 metres. Each spool of tape used for recording has to run for about half an hour at a speed of 90 metres a minute, so that some 2 700 metres are required. This means that even in a new tape there will be at least two joints, which are made by means of silver solder.

In the past, if breaks occurred in the tape during normal running, soft-soldered joints were made. A system of welding the tape which is now being tried out, however, gives most encouraging results.

Design of Recording Machine

The mechanical requirements to be fulfilled by the machine may be summarized as follows:—

(1) The tape must move through the heads at a constant velocity during both the recording and the reproducing processes.

(2) The tape must be unwound from, and rewound on to, the spools without undue tension being applied to it.

(3) A practically instantaneous start from rest is desirable in order to facilitate the commencement of a reproduction at a predetermined cue.

(4) A rewinding speed considerably in excess of the forward running speed should be available so that two machines can be run continuously in tandem if necessary.

Experience has shown that the foregoing requirements are best covered by the use of three separate mechanical drives, one for unwinding the tape from the trailing reel, another for maintaining the velocity of the tape constant through the heads, and the third for winding the tape on to the leading reel. The constant-speed system is virtually isolated from the unwinding and winding systems by the provision of reservoirs, one preceding it and one following it, and the speed of the winding and unwinding motors is automatically regulated so that both reservoirs always contain a loop of tape.

These two motors are of the induction type, with their rotor windings brought out to three slip-rings and their brushes connected to external resistances arranged as a three-phase star-connected system. With the full resistance in circuit the speed of the motor is such as to make the speed of the tape less than it is in the constant-speed drive system, but provision is made for short-circuiting part of the resistance. The winding and unwinding systems thus each have two forward speeds, one greater and one less than that of the constant-speed drive. By causing the motors to alternate between their two speeds a sufficient loop of tape is always maintained in both reservoirs. The switching in each case is carried out by a relay, the operation of which is controlled by a gas-filled thermionic valve of the thyratron type. This consists essentially of a half-wave rectifier, but by applying sufficient negative bias to its control grid the anode current can be completely suppressed. Such a bias is normally applied and, the relays being unenergized, the unwinding motor runs normally at its higher speed and the winding motor at its lower speed. Therefore loops form in both reservoirs. When the loop of steel tape becomes long enough, it touches a contact at the bottom of the reservoir, which is connected to the grids of the associated thyratrons, and short-circuits the grid bias. Anode current then flows, causing the relay to operate and change the speed of the motor. The size of the loop is now reduced, but the process is checked when the tape is pulled clear of the contact, for the bias is thus reapplied to the thyratrons, causing the relay to release and restore the original condition.

The constant-speed drive system is not required during the rewind, and an automatic release clutch is provided for disconnecting it. The rewinding motor, running in the reverse direction and coupled to the tape-drive through a double-speed pulley, pulls the tape off the right-hand reel and feeds it into the large tape reservoir. The winding motor, with its direction of rotation reversed, now drives the left-hand reel on to which the tape is being rewound, and its speed is regulated as before by the thyratron circuit. The speed of the unwinding motor is not varied during the rewinding operation.

The trailing reel in both directions of working is restrained by a simple band-brake, and provision is made for increasing the brake tension in order to overcome the momentum of the reel when the machine is stopped.

The operation of the machine is controlled by a rotary gate switch which has five positions:—Off, 1st and 2nd wind, and 1st and 2nd rewind. The intermediate positions are introduced to ensure the correct operating sequence, and to prevent the formation of loops of tape in the reservoirs during the processes of starting and stopping.

The behaviour of the machine for the various positions of the gate switch is given in the schedule on page 282.

The performance of this machine shows a considerable improvement on that of earlier designs. The variation in tape velocity is not normally perceptible when listening to a musical recording.

Illustrations and references showing the general construction of the machine are given in Figs. 19–22 (see Plates 1, 2, 3, and 4).

SECTION (4)

Magnetic Recording Applied to Broadcasting

As the technique of broadcasting has developed during the last few years, so the demand for recording

SCHEDULE OF OPERATIONS

Position of Gate Switch.	Action.
Off.	Power is applied to the heaters of the thyratron cathodes, and to the metal-oxide rectifier circuit providing the grid bias.
No. 1 *Wind.*	H.T. is switched on to the thyratrons and the L.T. and grid-bias supplies continued. No. 1 motor is switched on for forward running at its lower speed, engages with the belt drive of the R.H. reel by means of No. 1 automatic dog clutch, and tends to drive this reel in an anti-clockwise direction. Maximum braking is applied to the trailing (L.H.) reel.
No. 2 *Wind.*	The conditions of the *No.* 1 *Wind* position are maintained, except that the braking on the L.H. reel is reduced to the normal running value. No. 2 motor runs forward at its higher speed, engages with the lower-geared belt system through No. 2 automatic dog clutch, and thus causes No. 2 tape drive to pull the tape off the L.H. reel and feed it forward at a rate slightly higher than the feed of the main tape-drive system. No. 3 motor is switched on and runs forward at its constant speed of 250 r.p.m., pulling the tape through the heads at a steady rate of 90 metres per minute and feeding it into No. 1 reservoir from the R.H. side. The higher speed of No. 2 motor is maintained until the tape loop in No. 2 reservoir touches the thyratron contact, thereby short-circuiting the grid bias and causing the operation of No. 2 relay. The speed of No. 2 motor is thus changed to the lower value, which allows the tape loop in reservoir No. 2 to be reduced. The lower speed is maintained until the loop ceases to make contact with the thyratron control contact, whereupon the motor reverts to its higher speed and the process is repeated. The R.H. reel, driven by No. 1 motor and now having no tape tension to restrain it, begins to wind up the tape, but at a lower rate than it is being fed into No. 1 reservoir by No. 3 system. However, when the loop in No. 1 reservoir touches the thyratron contact, No. 1 motor runs at its higher speed and continues to do so until the tape loop in No. 1 reservoir is pulled off the contact. The speed then returns to the lower value and the process is repeated.
No. 1 *Rewind.*	H.T. is switched on to the thyratrons and the L.T. and grid-bias supplies are continued. No. 3 drive system clutch is disengaged. No. 1 motor is switched on for reverse running at its lower speed, engages with the higher-geared belt drive of the L.H. reel by means of No. 1 automatic dog clutch, and tends to drive this reel in an anti-clockwise direction. Maximum braking is applied to the trailing (R.H.) reel.
No. 2 *Rewind.*	The conditions of the *No.* 1 *Rewind* position are maintained, except that the braking on the R.H. reel is reduced to the normal running value. No. 2 motor runs backward at its higher speed, engages the higher-geared belt system through No. 2 automatic dog clutch, and thus causes No. 2 tape drive to pull the tape off the R.H. reel and feed it into No. 1 reservoir from the L.H. side at approximately twice the normal forward speed. No tape loops occur in No. 2 reservoir, hence the speed of No. 2 motor is not controlled. The L.H. reel, driven by No. 1 motor and relieved of restraint by the existence of the loop in No. 1 reservoir, then begins to wind up the tape at a low rate until the loop in No. 1 reservoir touches the thyratron contact. When this contact is made No. 1 motor runs at its higher speed and continues to do so until the loop in No. 1 reservoir is pulled off the contact. The speed then returns to the lower value and the process is repeated. No. 3 motor does not run at all during the rewinding process.

facilities has increased. New ideas of presentation have materialized and the inauguration of the Empire service called for some means of providing programmes, other than that of direct transmission from a studio.

Three different systems of recording are in use at the present time, as it is impossible to fulfil all the technical and programme requirements with any single system.

The programme service requirements are many and varied. It must be possible to make a record of a programme lasting for some hours, take extracts from it, mix, fade, and superimpose extracts from other recordings, and produce what is termed a composite record. It is also necessary, in some instances, to make a number of copies of a record.

The types of recordings can be divided into two groups—permanent and non-permanent.

Permanent recordings are made of items of historic interest, such as national ceremonies and speeches; effects records used to provide backgrounds in the production of plays, and so on.

The non-permanent recordings include those of rehearsals, and of home programmes for subsequent transmission on the short-wave Empire service. This may involve four or five reproductions to cover the various zones, after which the record is of no further interest and may be destroyed.

The technical considerations include:—

(1) All factors involved in the production of what is often termed " good quality."

(2) The possibility of the duplication of the original record without noticeable deterioration of quality and without resorting to re-recording.

(3) The time which must elapse before the first reproduction can be obtained.

(4) The reliability of the system as a whole.

(5) The reliance which can be placed on the success of any individual recording.

(6) The ease of operation of the system.

(7) The permanence of quality of a record, (*a*) during storage and (*b*) after repeated reproduction.

(8) The suitability of the records for storing from the point of view of weight, size, etc.

If consideration is given to the matter, it will be seen that magnetic recording on steel tape fulfils a number of the programme and technical requirements. It is very useful in cases when non-permanent records are required, as the tape can be used repeatedly. It is also applicable in the case of permanent recordings, as the quality does not appreciably deteriorate after repeated reproductions. The records are, however, large and weighty, and occupy a considerable space when stored.

The system is particularly suitable for recording programmes of long duration which are required for subsequent reproduction in their entirety. It is not convenient, however, in cases where it is known that a number of extracts will be required from the record to form a shortened version of the original, since it is undesirable to cut and join the tape. This difficulty can be overcome to a certain extent by re-recording, but a slight deterioration of quality is likely to occur as a result of this process. Furthermore, it is generally more convenient to employ a recording system which is particularly applicable to this type of work.

Description of a Tape Recording Channel

Each recording channel at Maida Vale comprises two machines and two complete sets of amplifiers and associated apparatus, which are accommodated in two rooms. One is known as the apparatus room and contains two machines, amplifier bays, associated apparatus, and a loudspeaker for monitoring purposes. The other is known as the control cubicle, in which there is a second loudspeaker and a control desk from which the control engineer can see into the apparatus room through a double glass window. A schematic diagram is shown in Fig. 23, to which the references apply.

The programme originating in a studio or at an outside broadcast point is transmitted by line via the control room at Broadcasting House to the control room at Maida Vale. It is then distributed by isolating amplifiers to the recording channels. The programme is next passed through a control potentiometer in the control cubicle, and thence to the two recording amplifiers (Rc) the inputs of which are connected in parallel through a key switch (Rec. C.O.), which can be used for change-over purposes. Each amplifier incorporates suitable frequency-discriminating networks between the first two stages, and has a final push-pull stage. The output of the amplifier can be connected by means of a switching key to either of the recording heads associated with the appropriate machine, the steady demagnetizing current being introduced into this circuit.

Either of the two reproducing heads associated with the machine can be connected to the input of the three-stage reproducing amplifier (Rp) by means of a key. This amplifier embodies the discriminating networks necessary to produce an overall frequency characteristic that is sensibly flat up to the cut-off frequency.

Two separate output circuits are provided. One of these is used to supply the programme to the Maida Vale control room through a change-over unit (2 Ch. Fade Unit) and thence to Broadcasting House. The other supplies the loudspeaker amplifiers associated with the loudspeakers (L.S.) in the apparatus room and the control cubicle. Switching arrangements are available in both these rooms, to enable the loudspeaker to be connected either across the incoming programme or across the output of either of the two reproducing amplifiers. The listening levels can be balanced by means of volume controls. A programme-level indicator (P.M.) is available for measurement of the level at any point in the chain.

Since the recorded programme is reproduced a fraction of a second after the recording actually takes place, the quality of this can be readily compared with that of the incoming programme. It has already been pointed out that this facility enables the recording engineer to determine and adjust the recording level by listening to the programme after reproduction, since it is necessary to effect a compromise between limits imposed by signal/noise ratio and distortion.

The above method of monitoring has been found to be the most satisfactory in practice, but various forms of visual indicators have been tried from time to time. One of these consisted of a neon indicator operated indirectly by the a.c. voltage developed across a resistance in series with the recording head. This indicator was so adjusted that faint flashes occurred in the lamp when the maximum permissible recording level was approached, and bright flashes when the level producing overloading was reached. There are, however, certain drawbacks to such a system. It must be realized that no reduction of the value of available signal/noise ratio can be tolerated. In fact, in some instances it is necessary when recording to reduce the volume range of the programme which has already been controlled for transmission purposes.

In order that an indicator of the type described above should be of assistance, the tapes used for recording must be absolutely uniform as regards the maximum permissible recording level which can be applied. If this is not the case, the visual indicator must be so adjusted that a margin is allowed for the non-uniformity of the tapes, and this means that the maximum permissible recording level is not supplied to some tapes, with a consequent reduction in signal/noise ratio.

Two engineers are required for each recording channel, one in the control cubicle and the other in the apparatus-room. The former checks the quality of the recording and controls the recording level, while the latter is in charge of the machines and apparatus. A system of illuminated indicators is used between the control cubicle and the apparatus room, which enables the control engineer to give the necessary directions to the engineer in charge of the apparatus.

When preparing for a recording session, the pole-pieces for all the heads must be carefully selected, and a test recording must be made to ensure that the performance is satisfactory.

Both machines in the recording room are kept ready for immediate use, whether the recording to be carried out requires one spool of 30 minutes' duration or more. In the case of a recording lasting over 30 minutes it is necessary to make a change-over from one machine to the other. This is usually carrieed out in the following way. When the spool on the first machine nears the end of its run the second machine is started up, and at a suitable passage in the programme, preferably during a pause between two items, the recording is changed from the first machine to the second. The tape on the first machine is then rewound, and a new tape put into position ready to take over if necessary. In the event of a fault of any kind developing while the first machine is in operation, the second machine is immediately started up and takes over the recording. If, on the other hand, a fault develops on the second machine while the first is being rewound, it is necessary to continue the recording on a machine from another channel. No change-over is attempted in this case, the spare machine being brought into operation as soon as possible.

In the case of a reproduction involving more than one spool of tape, the machine allotted for the reproduction of the second spool is set up in such a way that there is just enough tape prior to the commencement of the recorded programme to allow the machine to reach normal speed before the recorded section reaches the reproducing head. An appropriate passage is selected towards the termination of the recording on the first spool, to act as a cue for the starting of the second machine. The finding of cue passages is simplified by the provision of indicators coupled to No. 2 driving system (Figs. 19 and 21, Ref. 49, Plates 1 and 3).

When a programme is of particular importance, simultaneous recordings are made on two machines. These may be the two machines comprising one channel when the programme is timed to last for less than half an hour, otherwise it is necessary to use two complete channels.

The signal for the commencement of a recording or reproduction can be given by a system of cue lights, which are operated either from the control rooms at Maida Vale or Broadcasting House, or directly from a

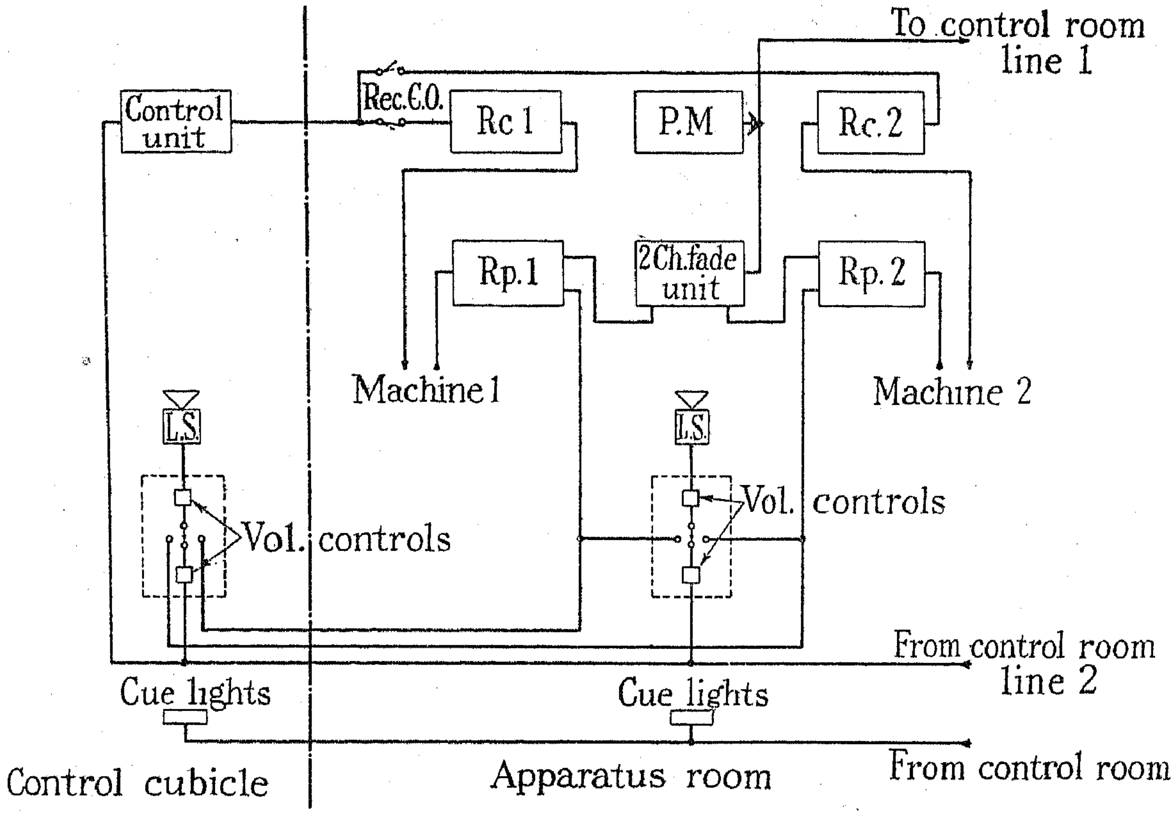

Fig. 23.—Block schematic of recording channel.

studio. Alternatively, the recording or reproduction can be arranged to commence on a predetermined cue-passage occurring during a normal transmission.

It is sometimes necessary to obliterate a certain portion of a recording. For instance, in the case of a programme recorded during the day for transmission to the Empire at night, an announcement such as "This is the London Regional Programme" may occur, and before the recording is transmitted to the Empire this must be wiped out. This is accomplished by inserting a wiping pole-piece in the second reproducing head and using it as a wiping head. A unit consisting of a battery and a variable resistance with a spring-loaded control is connected in series with this head. The resistance is open-circuited in the "off" position of the control, and a condenser is connected across it to prevent clicks due to sudden changes of flux. The tape on which the passage to be wiped occurs is passed through the machine with the first reproducing head in use in the normal manner. At the appropriate moment, the control completing the circuit through the second reproducing head is operated and the unwanted portion is wiped out. At the end of this unwanted portion the control is released and the remainder of the recording is unaffected. It is then possible to record an alternative announcement on the portion of the tape which has been wiped. By this means the wiping process may be commenced practically instantaneously or the programme may be faded out gradually.

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DISCUSSION BEFORE THE WIRELESS SECTION, 1ST DECEMBER, 1937

Mr. N. M. Rust: While an ideal recording system does not exist, there are several features of magnetic recording which stand out. There is no other recording system, for instance, whereby it is possible to "rub out" in the middle of a programme and to record something else. With magnetic recording one also has the ability to play back instantaneously and to make a delay playback at any time from 0·1 sec. up to 1 minute after the signal.

The ability to rub out and re-record could be applied to recording for stenographic purposes. There is the possibility in a large organization of a recording room linked up with the offices and the typists in such a way that the staff can record their letters, have them played back again, and then rub out and correct them. Whether such a system is commercially practicable at present I do not know, but if it could be developed it would certainly be a great boon in large offices.

With regard to the ability to play back at any delayed time, one fairly obvious application which seems quite a simple matter is the production of artificial echoes for broadcasting. But, if it were done in the ordinary way with a single reproducing head, the system would not give a natural effect, because such an arrangement does not simulate the reverberations which occur. The only feasible system would be one having two or three reproducing heads delayed at different times behind the recording head, and with the delay periods arranged in relation to the reproduction characteristics. The heads and the amplifiers associated with them would have to be split into bands, the head nearest the recorder passing the higher frequencies and the head farthest away passing the lower.

In developing the recording machine to the point where speed variations were not noticeable in commercial production, even higher standards were obtained under laboratory conditions. One of the difficulties of magnetic recording is that mechanical considerations necessitate a certain size of tape drive wheel. If the wheel is made smaller it does not hold the tape well, and if it is made bigger the inertia effects in the tape wheel itself become serious. It happens that the period of variation which the ear most notices is just about the period of one revolution of the tape wheel, which makes it necessary to take great precautions to ensure a steady drive.

By using a synchronous direct-drive motor instead of a high-speed motor and gearbox, we avoided "flutter" troubles. The electrical analogue of such an arrangement is a generator working through an inductance. The flexible coupling interposed between the direct drive and the flywheel is equivalent to a condenser, and the flywheel itself is equivalent to a big inductance. The inertia of the tape-wheel system is equivalent to a small inductance, and the aim is to keep this small relative to that represented by the flywheel, and also to make the flywheel equivalent to a damped inductance. Similarly, by using material of high internal friction, we attempted to get all the damping we could in the coupling.

In the experimental work to get rid of the troubles due to irregularities, we used two forms of check arrangements. The first consisted of a stroboscopic disc on the end of the tape wheel, and a sodium lamp which was energized from the mains and timed from a special circuit. The stroboscopic marks stood out so clearly that it was possible to use a low-power microscope for observing the fluctuations. The other method used for the final check was an oscillograph method, suggested by the B.B.C. engineering staff. It consisted in controlling the horizontal sweep of the oscillograph by a sawtooth time-base which was locked from the recorded tone, and obtaining the vertical sweep from the reproduced tone. Any irregularity in the speed caused a displacement of the pattern.

An interesting piece of apparatus used in the development work was a continuous-band tape machine. This had a form of reservoir which allowed of the use of a tape taking up to ½ minute to run through. The tape had a joint in it, of course, and was so arranged that we could easily reverse it. This device enabled us to listen to speech backwards. We would take a simple sentence and try to say it backwards; if we were successful, the record would come out as the original sentence, which seems to show that intelligibility of speech, at least in English, is not dependent on transients (which surely cannot be generated backwards) to the extent that one would think.

Mr. H. L. Kirke: Some of the effects of demagnetization are not easy to understand, and I should welcome further explanation of these.

I should like to mention the difficulty of getting steel manufacturers interested in the problem of steel tape for magnetic recording. The trouble is that the cost of research in this subject is very high, and relatively only a small quantity of tape is required. For this reason we have more or less had to adhere to the products of one firm. Another point on which the authors do not say very much is the question of the pole-pieces. Further details of these would be welcome.

Regarding the subject of jointing, it would be interesting to know how the welding experiments referred to in Section (3) have turned out.

In connection with constancy of speed and size of apparatus, there is a great difference between the requirements of an apparatus for reproducing music in ordinary broadcasting channels and that of apparatus which is merely required to reproduce speech. Speed constancy in music requires far greater accuracy than in speech, and it is necessary to use much larger apparatus in order to obtain that speed constancy. For speech records in offices and the like, a much smaller machine than the one described in the paper would be satisfactory.

Mr. F. H. Dart: I consider the machine described in the paper to be a reliable piece of mechanical apparatus. In the past year machines of this type have been "on the air" for reproducing programme material 1 957 hours. The total breakdowns over the same period only amount to 39 minutes 28 seconds, equivalent to 0·033 % of the programme time. Of these breakdowns, none can be directly attributed to the machines: 26 minutes 33 seconds of the breakdown time was due to tapes breaking at joints, the remainder being due to amplifier or other electrical trouble.

Regarding the authors' statement that the single-pole and the double-pole methods of working can both be made to give satisfactory results, I would recommend the use of the single-pole method. In the past our tape joints have taken the form of soft-solder lap joints, and it is my opinion that breakdown has resulted from the pole-pieces catching in these joints. With the single-pole system, the edge exposed to the pole-piece can be so arranged that it is on the opposite side of the tape from the pole-piece, and in this way the trouble can be materially reduced.

No mention has been made of the wear of tapes. We have many in service which have carried out 60 recordings; they must have been reproduced many hundreds of times, and yet they are still in good condition. A tape which was delivered from the manufacturers just over a year ago, and on receipt was calibrated both for background noise and magnetic properties, after a year's service and 30 recordings showed an increase of 6 db. in background noise. This was first thought to be due to general wear on the tape, but was subsequently found to be due to foreign matter, and by suitable cleaning the tape was restored to its original state.

There is one question I should like to ask the authors. The recording curve A in Fig. 16 (double-pole system) is relatively flat compared with the recording curve A in Fig. 17 (single-pole system), whereas the reproducing curve C in Fig. 16 (double-pole system) has a sharply-rising characteristic while the corresponding curve for the single-pole system (Fig. 17) is a falling one. It would therefore appear that the background noise on a double-pole system should be materially greater than on a single-pole system, and I should be interested to know whether this is the case.

Dr. L. E. C. Hughes: While working on the development of a magnetic reproducing machine, which consisted of a steel tape clamped on the edge of a wheel, my associates and I obtained some 12 000 reproductions before the level dropped by about 3 db.; the intelligibility was maintained, but the quality was only of telephonic standard. In this machine, an arrangement provided for the lifting of the pole-tips from contact with the tape on the passage of a joint.

With ordinary steel-tape we noticed a threshold effect, i.e. a definite applied level had to be exceeded before any registration was effected; also with increasing applied level the registration level fell off, on account of saturation. Did the authors experience such effects in the early stages of development?

I wish to protest against the physical explanation of demagnetization of steel, using the theoretical conception of magnetic poles. These do not exist physically, and are useful only for defining an arbitrary magnitude of magnetic flux, which, like its electric counterpart, current, is a sufficient conception for explaining magnetic phenomena.

Mr. Donald McMillan: Five years ago we in the Post Office Engineering Research Department acquired a magnetic-recording apparatus which we employed to introduce a time-delay into transmission circuits. It had certain differences from the equipment described in this paper, and I should be interested to have the opinion of the authors on those differences. The arrangement of the equipment was simple. It consisted of a continuous loop of tape which passed first through a recording head, then through a reproducing head, and finally through a wiping head; and the time-delay could be controlled by moving the recording head relative to the reproducing head.

The method adopted for wiping out was, however, quite different from that described by the authors. The wiping head consisted of a solenoid with its axis along the tape, and the tape was entirely demagnetized by passing alternating current through this solenoid. The tape was then magnetized to a certain steady value by the recording head, which had direct current passing through it. The recording was presumably effected by alternating the value of the magnetization around the value produced by that direct current. In the system described by the authors, on the other hand, the wiping head saturates the tape, and the recording in effect reduces the magnetization of the tape.

I am interested in the description of the present apparatus from the point of view of the signal/noise ratio and range of amplitude permissible. A recently-published description of a good type of optical recording system states that a ratio of peak-to-valley intensity in music of 55 db. was reduced effectively to 38 db. by the use of this recorder. Can the authors quote any comparable figure for their equipment?

With regard to the signal/noise ratio, a figure of 35–45 db. is considered poor by telephone engineers, whereas the reproduction which we have heard from the author's apparatus and with which we are familiar from broadcasting is anything but poor. I should like to know the explanation for this. Further, I am not able to relate the figure of 35–45 db. to Fig. 14. Perhaps the authors could give some further information as to how that signal/noise ratio was measured. I presume that it was measured with some form of programme meter, measuring first of all the signal and then the noise.

With our old type of apparatus, which used rather thicker pole-pieces than those described in the paper, we had great trouble due to wear of the pole-pieces. I notice that the pole-pieces described by the authors are sharpened down to 0·06 mm., and I should like to know what is the effect of wear upon their performance. Presumably the degradation obtained as they wear is the conventional type associated with any recording system, namely lack of high frequencies and increase in noise. Does this constitute a serious cause of trouble, and do the pole-pieces need changing often?

Mr. L. S. Anand: Can the author give any information about the design and the thickness of the tape? I imagine that while there is longitudinal recording there is also transverse recording, and this may distort the regularity of reproduction. Is the thickness of the tape based on mechanical limits, and should the tape be as thin as possible? Is there an optimum value for the coefficient of modulation used?

Mr. L. C. Stenning: In view of the advantage derived in the way of cost and storage by reducing the speed of the tape, I should like to draw attention to some recently-published American work* in which the tape was magnetized perpendicularly instead of longitudinally. The quality and frequency-range claimed were about the same as for the authors' machine, and this result was secured with a speed of about 16 in. per sec., instead of 1·5 m. per sec.

Mr. E. L. E. Pawley: We all know the advantages of negative feed-back in an ordinary amplifier system: one takes part of the output and feeds it back into the input, and, if the phases and magnitudes are right, one is thus able to cancel out some of the unwanted effects which occur in the process of amplification. In the case of magnetic recording, would it be possible to take part of the output from a reproducing head and inject it back into the recording head (or into an auxiliary recording head) during the recording process in such a way as to cancel some of the non-linear distortion and also some of the noise which arises in recording? An obvious difficulty is that the phases will not be the same for all frequencies, but it might be possible to put this right by a phase-compensating network or by running an auxiliary loop of tape in synchronism with the main tape.

Mr. H. Bishop: I should like to mention the use of magnetic-recording equipment for business purposes. The original machine of Dr. Stille was developed by him and marketed as an office machine in 1925, because at that time the need for a recording process for broadcasting had not asserted itself. The machine had two forms. One used a steel tape 6 mm. wide, compared with 3 mm. on the machine described in the paper, and the other, a much smaller affair, used a wire of 0·25 mm. diameter. Both gave what would now be called very poor quality, but in those days the results were considered not at all bad. No further development work was done on the machine until it became available in this country in 1930.

More recording in connection with broadcasting is done in Germany than in this country. The German broadcasting authorities use magnetic-recording machines installed in vans, and the results are, I believe, fairly successful. In this country the vans used by the B.B.C. are equipped for cellulose-disc recording.

An important requirement of a recording system when used for broadcasting is the ability to edit the records. For example, during a football match a commentary of an hour or so may be recorded, but only the specially exciting parts may be wanted for re-broadcasting in the news bulletin the same evening. For this class of work, therefore, editing is essential. A magnetic-recording system is not quite so convenient in this respect as a disc system, but on the other hand the former has the advantage of being able to repeat a long programme without interruption. Further, the tape can be used an indefinite number of times, and this is of particular value for the short-wave service, where the programmes are radiated 4 or 5 times in a period of 24 hours, after which they are not wanted again.

Messrs. A. E. Barrett and **C. J. F. Tweed** (*in reply*): The experiments relating to the welding of tapes to which Mr. Kirke refers have proved satisfactory. During the process of welding, however, the tape becomes brittle and subsequent annealing is necessary. This unfortunately alters the magnetic properties of the tape. The noise due to this and to the mechanical imperfections of the joint is considerably less serious than that produced by a soldered joint, which is comparatively uneven and mechanically inferior.

Mr. Dart's remarks concerning single-pole recording (Group 1, Fig. 11) and double-pole recording (Group 2*b*, Fig. 11) are important since they have considerable bearing on the operation of a system with which he is concerned. There is little difference between the results obtained with these two systems, but listening-tests indicate that the quality of reproduction is superior when using the double-pole system. With the latter it is possible to record at a slightly higher level at the higher frequencies, though at the lower frequencies the converse holds. As we are chiefly interested in the level of the recording at the higher frequencies from the point of view of surface noise, this point is in favour of the double-pole system.

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* *Bell System Technical Journal*, 1937, vol. 16, p. 165.

The statements referring to the recording curves for the S.P.I. and D.P. systems appear correct at first sight, but it must be remembered that the signal/noise ratio is dependent on the absolute level of recording, and in practice it is found that the increase in signal/noise ratio which might be expected is not realized. The results of tests under service conditions show that for a given quality of reproduction the recording level for the S.P.I. system is lower than the corresponding level for the D.P. system. This results in practically the same signal/noise ratio being obtained for both systems.

It is probable that, during the experiments referred to by Dr. Hughes, recording was carried out near the state of zero magnetization, in which case the effect mentioned might be expected on account of the low initial permeability of the tape. We regret that Dr. Hughes takes exception to our physical representation of the demagnetization of steel.

The method of wiping mentioned by Mr. MacMillan indicates that the tape is in a state of zero magnetization when leaving the wiping head, and it follows, therefore, that the recording takes place on a portion of the initial magnetization curve instead of a portion of the largest hysteresis loop, and ideally a shorter straight portion would be available for the recording process. Since there are other limitations to the possible amplitude of recording, the linear ranges obtainable with the two systems may not be widely different. With regard to a comparable figure for peak-to-valley intensity which may be obtained, this varies considerably with different tapes, but is of the order of 30 to 35 db. The signal/noise ratio was measured with various types of programme meter. Some of these meters had a long, and others a short, charging time, but the results obtained agreed within one or two decibels. Measurements on the tapes used at the demonstration actually gave a signal/noise ratio of approximately 40 db. The energy contributing to noise is chiefly confined to the high frequencies, and if measurements were made with a cut-off frequency of 3 000 cycles the signal/noise ratio would be higher. If an attempt is made to estimate the maximum signal/noise ratio from the curves of Fig. 14, allowance must be made for the amplitude/frequency relationship which occurs in music, and since the amplitudes at 4 000 cycles are considerably lower than those occurring below 1 000 cycles it would appear reasonable to estimate the signal/noise ratio from one of the lower-frequency linearity curves. The curves in Fig. 14 were not taken with a particularly good tape—probably one which gave a signal/noise ratio of 36 db. The effect of pole-piece wear is in general to reduce the high-frequency response, and also the noise, since this is noticeable chiefly at the higher frequencies. If, however, the pole-pieces become jagged due to passing over a bad joint, then the quality is liable to suffer. Pole-pieces are checked before each recording or reproduction, and their life is largely dependent upon the nature of the joints in the tape.

In reply to Mr. Anand's questions concerning the thickness of the tape, this dimension (0·08 mm.) was originally determined by considerations of mechanical strength and manufacture. Experiments have been carried out recently using tape of a thickness of 0·05 mm., but the results have been inferior to those obtained with the 0·08 mm. tape. The expected reduction in self-demagnetization effects was not realized, owing probably to non-uniformity of magnetization at the higher frequencies referred to in Fig. 15.

We have carried out experiments on a system similar to that referred to by Mr. Stenning, and the results were inferior to those obtained with the D.P. or S.P.I. systems. We found that the adjustments which were necessary to achieve satisfactory results were much more critical, which is an added complication from the point of view of a recording service.

The suggestions outlined in Mr. Pawley's remarks are very interesting, but their application presents serious practical difficulties.

DIRECTIONAL RECORDING OF RADIO ATMOSPHERICS*

By F. E. LUTKIN.

[From the National Physical Laboratory.]

(*Paper first received* 22*nd September, and in final form* 22*nd November*, 1937.)

SUMMARY

The paper describes an improved recorder for indicating the direction of arrival of transient impulses continuously throughout the day. The polar diagram of the receiver has a width of 20° and is unambiguous. The analysis of three years' records shows that most of the atmospheric disturbance reaching a station in England arrives from the west or south-west, but that during summer afternoons sources to the east and south-east are productive together with storms of a purely local character. The disturbed azimuths appear closely related to the bearing of the great tropical thunderstorm centres, but the intensity of disturbance from each is dependent on the ionization conditions prevailing over the path to the receiver, at the time each region is productive. Curves are given from which the probable intensity of atmospheric in any direction at any time may be roughly determined.

INTRODUCTION

In a paper entitled " Directional Recording of Atmospherics," Watson Watt† has described the recorder used for some time in the work of the Radio Research Board. Its purpose was to register throughout 24 hours the azimuth of arrival of the electrical impulses called variously " atmospherics," " strays," etc. In the course of analysis of the records from this recorder, it became evident that in many cases atmospherics were arriving from more than one direction, and the physical significance of the results was being masked by the inability to determine more than the mean azimuth of disturbance when two or more streams were simultaneously active.

The improvements outlined in the present paper were originally suggested in the summer of 1927, but it was not until 1930 that time was found in the programme to proceed with the development of the instrument. Since then, and until the middle of 1935, the apparatus has been in almost continuous use, and has proved quite stable in operation and satisfactory in result.

It consists essentially of two frame aerials, referred to as the " recording frame " (R) and the " opposing frame " (O), mounted mutually at right angles on a common vertical spindle (see Fig. 2), and a short vertical aerial electrically associated with one frame aerial. The output from this combination, after amplification, is arranged to operate a pen-writing oscillograph recording on a drum rotating in step with the frames. The mechanical design was to a large extent governed by available parts from the older model, and since the equipment is housed in a small wooden hut at considerable distance from trees, telegraph wires, wire fences, electric cables, etc., which might introduce lateral deviation of incoming signals, it is necessarily battery-operated.

PRINCIPLE OF OPERATION

Let us consider the recording (R) frame and its amplifiers alone. Here we have a normal frame direction-finder in which a steady stream of atmospherics of constant amplitude produces in the oscillograph coils a current which at any instant will be $I \cos \theta$, where θ is the angle between the instantaneous position of the plane of the rotating frame and the azimuth of the atmospheric stream, and I is the output current when the plane of the frame coincides with the direction of arrival; since rectified current is fed to the oscillograph the armature will always be rotated in one sense, and this rotation is arranged to produce upward deflection of the pen. The type of chart obtained will then be similar to that from the older instrument, namely one with two wide bands of record, 180° apart, with very flat maxima.

From the opposing (O) frame, rigidly fixed at 90° to the other, the same source would produce an output equal to $I \cos (\theta + 90°)$, assuming set gains to be equal and θ the same angle as formerly. This output is connected to the oscillograph coils so as to apply a torque tending to rotate the armature in a direction opposite to that resulting from the output of the R set. The use of similar amplifiers ensures that the two torques are applied to the armature simultaneously, and the resultant torque is therefore proportional to $I[\cos \theta - \cos (\theta + 90°)]$. A stop provided below the pen prevents downward deflection, so that no record will result when $\cos \theta < \cos (\theta + 90°)$.

These steps are presented graphically in Fig. 1. Curve *a* shows the usual " figure of eight " diagram, drawn to cartesian co-ordinates, resulting from the R set only; the height of the curve is a measure of the amplitude of pen deflection obtained as the frame rotates through 360°; Curve *b* shows the output from the O set (at right angles to the R set) producing pen deflection downwards; *c* combines *a* and *b*, the dotted portion below the zero line being suppressed.

Now let the signal from the non-directional aerial be added to that from the R frame before rectification and adjusted in amplitude to be equal to it when the frame is set to receive maximum signal. The output from the R set is then $I(1 + \cos \theta)$ and follows the usual cardioid diagram. This results in the disappearance of one of the recorded sectors, where $1 + \cos \theta = 0$, and the record becomes unambiguous. Curves *d* and *e* show the unrectified currents in the frame and vertical aerials respectively, f combines the two, and g adds the combined output to that from the O frame $(f + b)$.

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* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† See Reference (1).

If now the amplification of the O set be progressively increased, the angle over which the output from the R set exceeds that from the O set will be correspondingly decreased. Thus the sector around the true azimuth of arrival over which a visible record is obtained may be narrowed to any desired width, and since the output from the O set is zero when that from the R set is at its maximum such reduction in sector width will not reduce the amplitude of the record at maximum, however narrow it is made. In practice a difference in gains of about 17 db. was found the most suitable value to employ, and h is the resultant curve with such values.

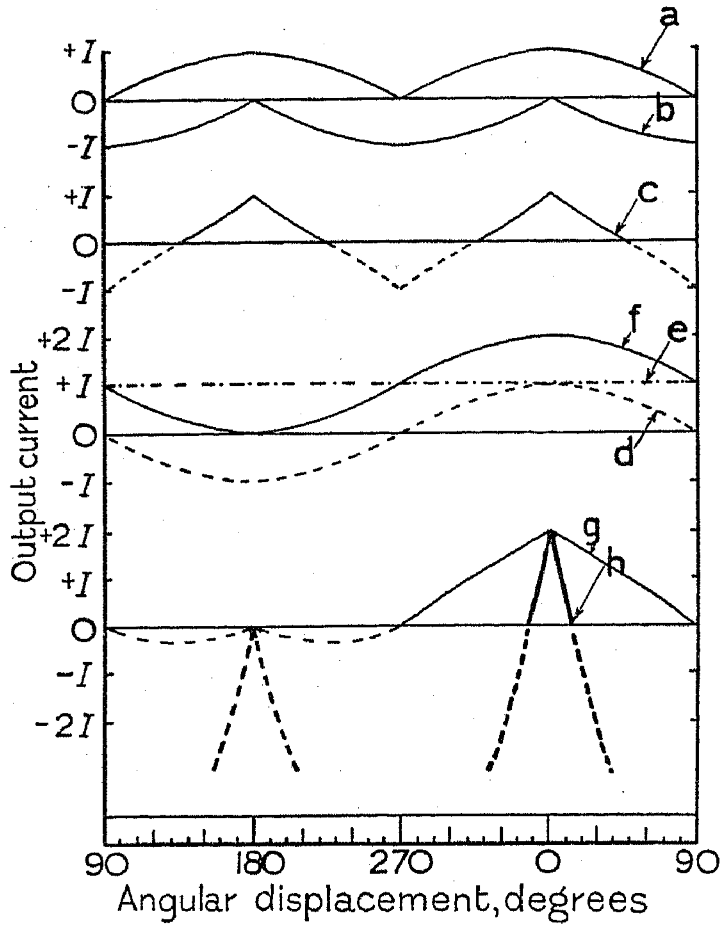

Fig. 1

Throughout these considerations it has been assumed that linear rectification is used. With the square-law rectification actually in use a further narrowing of the sector results; the output curves depart somewhat from those forming Fig. 1, but no fundamental change in the argument results.

DETAILS OF RECORDER

The general assembly of the recorder is seen in Figs. 2 and 2A. A pair of frame aerials (the recording frame R and the opposing frame O), mounted mutually at right angles on the vertical spindle A, are supported in ball-races in the timber framing B and rotated by a turret-clock movement C. The metal drum D carrying the recording paper is mechanically geared to the frame spindle, while an oscillograph E receives the amplified current from the aerials and moves a siphon pen P to record the atmospheric on the paper.

The Frame Aerials

The frame aerials, each 1 metre square, are wound in slotted paxolin rods 2·5 cm. in diameter, supported on aluminium cross-arms carried by diagonal arms of 2·5-cm. diameter aluminium tube which are secured by a central hub to the vertical spindle, of similar tube. The diagonal arms are broken near their ends, and an insulating section f is inserted to prevent the formation of closed conductive loops in the framing. The frames are wound with 170 turns of No. 26 S.W.G. copper wire, silk-covered, at 2·5-mm. spacing, terminated on insulators, from which leads are taken through the central spindle to the mercury slip-rings S. The centre point of each winding is similarly terminated, and the leads taken to a single point on the metal framing. The central spindle is suspended from a ball-race in the top of the teak framework B; its lower end passes through a radial race in the lower horizontal member and carries below it a flat circular porcelain disc in which are five concentric circular channels for mercury. Fixed contacts through the porcelain into each mercury " ring " terminate the four ends of the frame windings and the earth connection. Into the rings dip five iron rods mounted on an insulating block on the framework, and these are connected to screened leads which are taken to the tuning equipment.

The aerials each have an inductance of 0·034 H and a resistance of 107 ohms at 10 kc. per sec., and are adjusted to obtain zero mutual inductance.

Driving Clock

The frames are rotated four times per hour by a turret-clock movement C through a 5-mm. diameter leather belt drive. This was ultimately chosen, in view of its slight elasticity, as the best drive for producing a steady movement of the frames from the intermittent drive of the clock. A further steadying is obtained by coupling the belt pulley to the driving shaft by a spring.

Recording Drum

The hollow cylindrical drum, 15·3 cm. in diameter and 34·5 cm. long, and its supporting framework, which in the earlier instrument was connected directly to the frame spindle and mounted below the frame, is in this model supported on a bracket J (Fig. 2) attached to the side of the wooden framework and driven through a 1 : 1 bevel gearing and shaft G. Thus the drum rotates in synchronism with the frames, and any point on its surface may be referred to a particular orientation of the frame system. As the drum rotates it is lowered at the rate of 3 mm. per revolution by the screw s turning in the fixed nut n, so that a stationary pen traces out a helix on the drum surface.

The Chart

The recording chart consists of a sheet of glazed paper 49 cm. by 34 cm., secured around the drum by pasting at the 1-cm. overlap. On removal from the drum the helical track drawn by the stationary pen appears as a series of parallel and nearly horizontal lines, 3 mm. apart, and the upward deflections of the oscillograph pen caused by the atmospherics as short lines perpendicular to these.

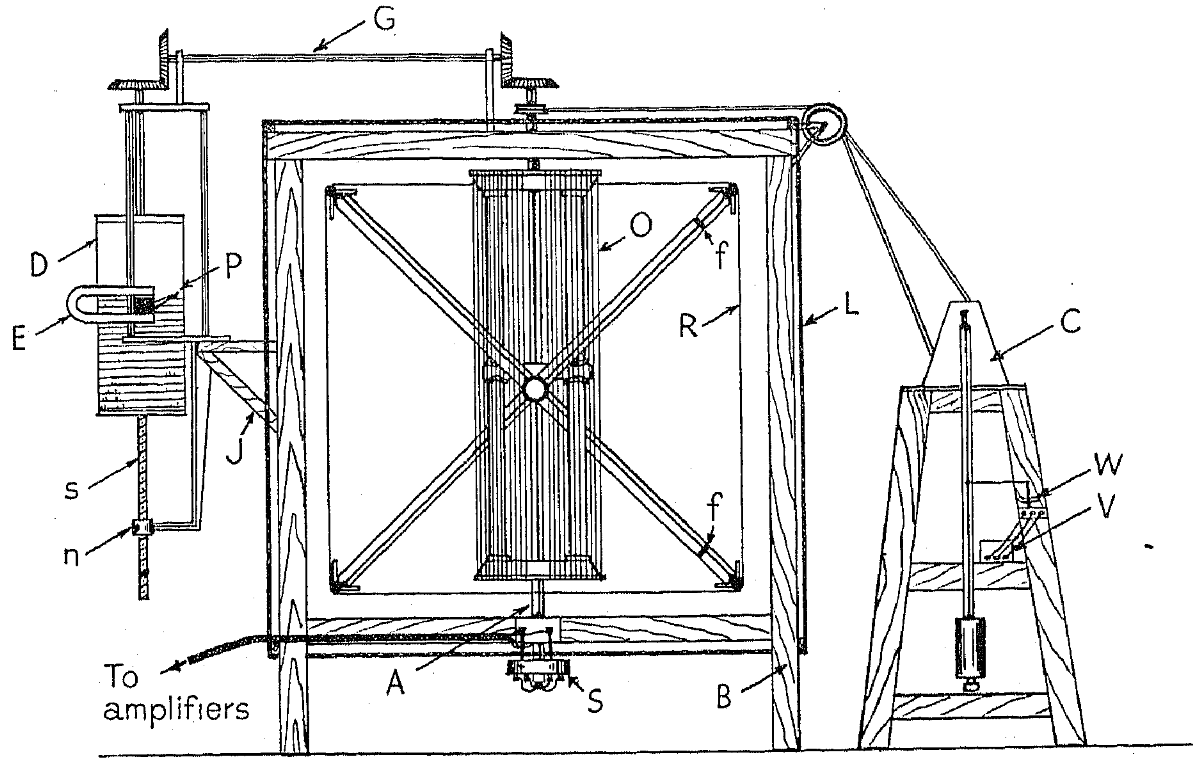

Fig. 2

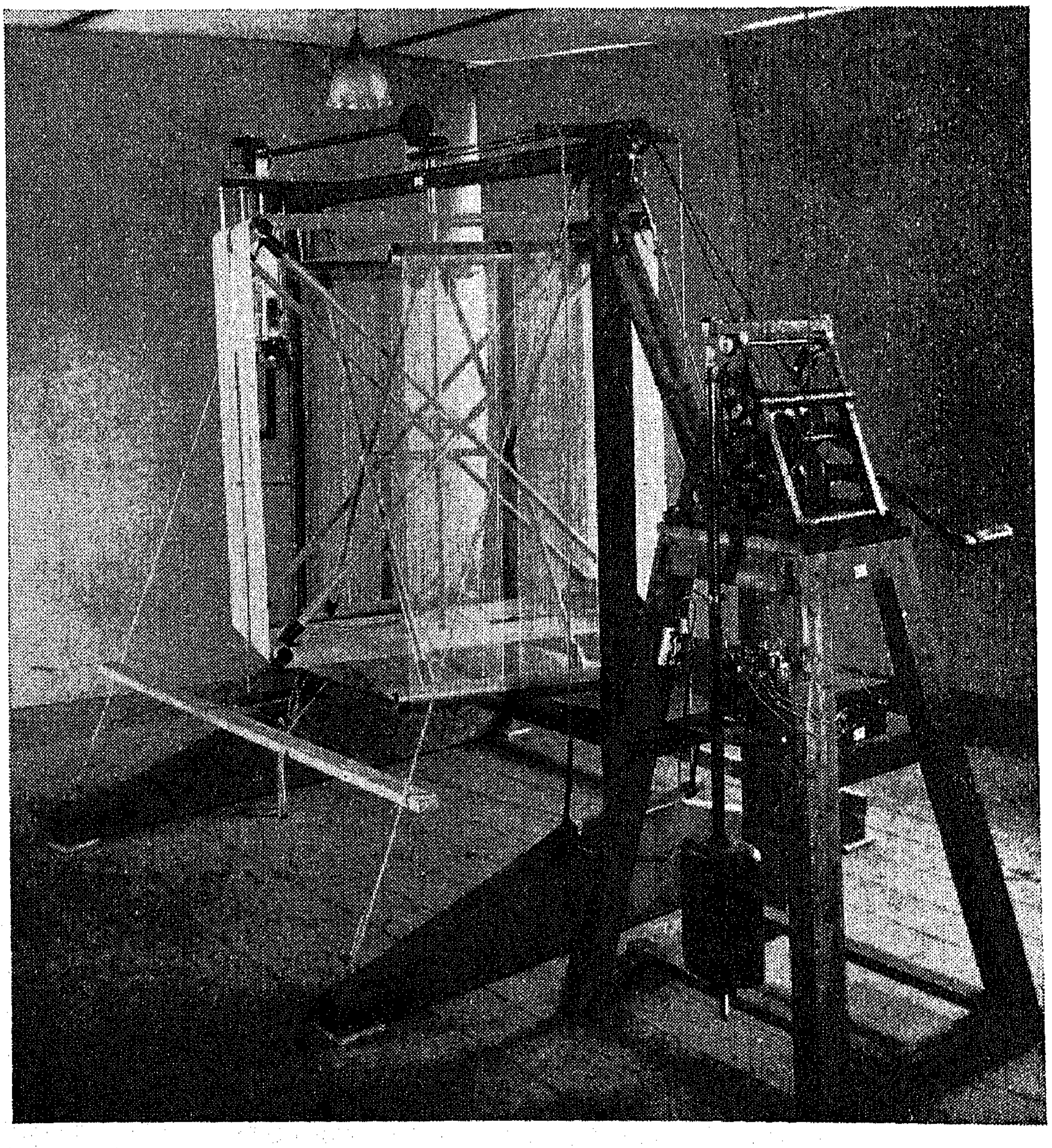

Fig. 2A

The Oscillograph

The Abraham–Bloch quadro-polar instrument with soft iron armature, used before, is again employed. It has four field windings each having a resistance of 2 500 ohms, two of these being connected in parallel in the output circuit of each amplifier, in such a manner that the flow of current in the pair connected to the amplifier associated with the R frame rotates the armature in a direction producing upward deflection of the pen, while current in the other pair from the O frame deflects the pen downwards. On the armature is mounted a light aluminium girder carrying the siphon pen. This pen consists of a short length of silver tube of 0·33 mm. bore with a writing tip of 0·12 mm. bore pushed into the larger tube. This gives a very fine line and does not tend to clog, as was found when the pen was constructed of fine bore tube throughout. A small stop fixed to the oscillograph prevents downward deflection of the pen, and the controlling torque of the oscillograph is adjusted so that in the zero position of the armature, under the steady anode current from the two sets, the pen rests lightly on this stop. To ensure uniform pen pressure on the drum surface, the oscillograph is mounted on a rotatable rod parallel to the axis of the recording drum. A small roller on the oscillograph immediately in advance of the pen is held on to the paper surface under the action of a spring-applied torque on the supporting rod, and the girder carrying the pen bent to give a certain but light contact between the pen and the chart. A small camel-hair brush is also provided to remove dust from the paper immediately in advance of the pen. This has proved very effective in preventing clogging of the pen due to dust collected from the paper surface.

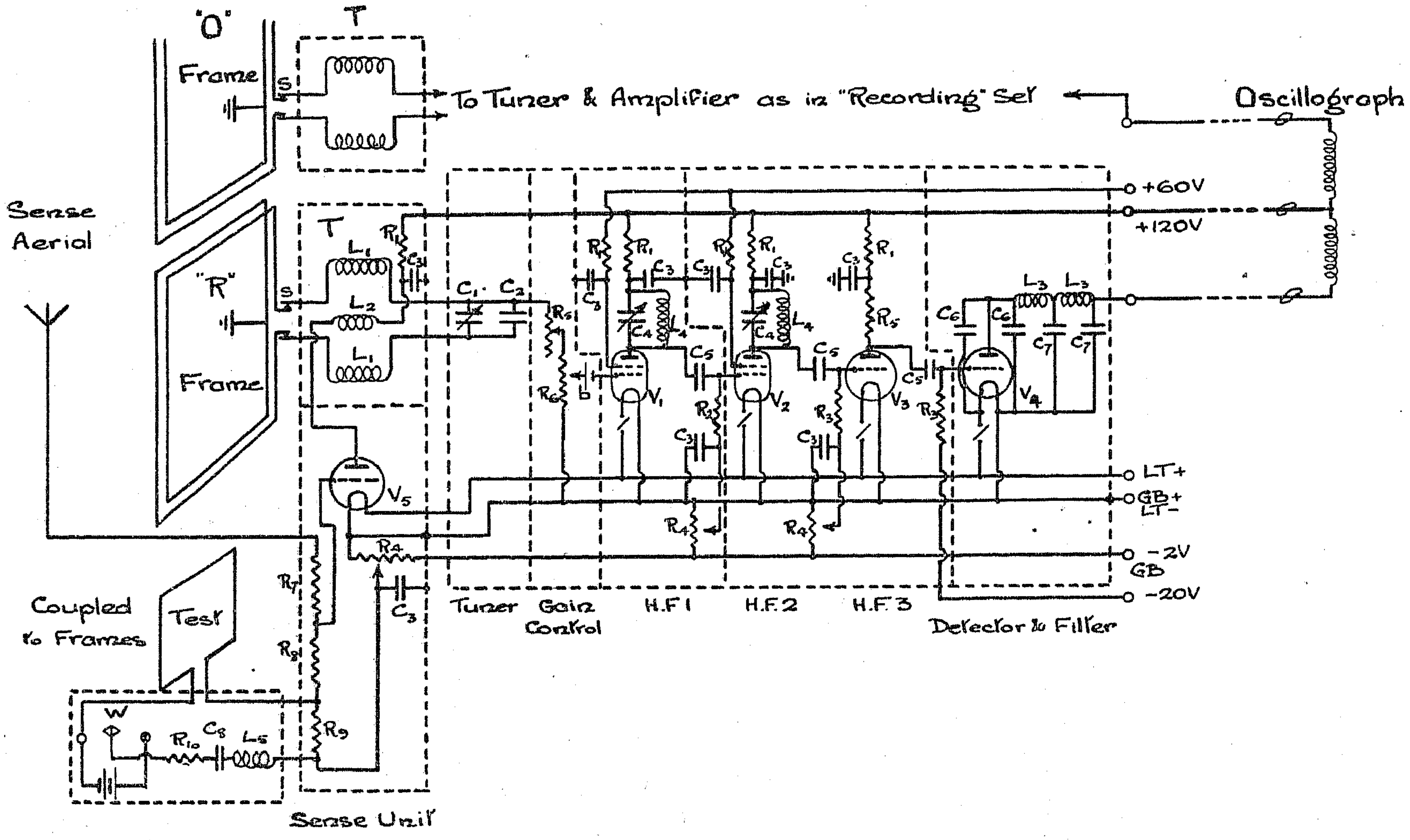

Fig. 3.—Narrow-sector recorder circuit diagram.

L.T. and H.T. batteries common to both sets. Separate grid-bias batteries for each amplifier.

R_1, 5 000 Ω.
R_2, 1 MΩ.
R_2, 0·5 MΩ.
R_4, 1 250 Ω.
R_5, 200 000 Ω.
R_6, 50 000 Ω.
R_7, 2 MΩ.
R_8, 0·1 MΩ.
R_9, 150 Ω.
R_{10}, 250 Ω.

C_1, 0·001 μF.
C_2, 10 × 0·0008 μF.
C_3, 1 μF.
C_4, 0·0013 μF.
C_5, 0·015 μF.
C_6, 0·25 μF.
C_7, 0·5 μF.
C_8, 0·5 μF.

L_1, 2 770 μH.
L_2, 88 640 μH.
L_3, 709 000 μH.
L_4, 510 000 μH.
L_5, 250 000 μH.

V_1, 215SG.
V_2, 215SG.
V_3, HL210.
V_4, P2.
V_5, H210.

Amplifiers

Similar amplifiers are provided for each of the two frames, and the schematic wiring diagram forms Fig. 3. Each has three stages of high-frequency amplification followed by a detector stage and filter unit. To ensure complete freedom from feed-back and cross-talk between amplifiers the separate units are enclosed in metal screening boxes and the connections are made throughout with screened leads. The two ends of the frame aerial are connected via the mercury slip-rings S and the split secondary L_1L_1 of the transformer T to the tuner unit. The transformer provides a means of coupling to the frame circuit the output from the vertical aerial which is discussed later. The tuner unit consists of a bank of ten fixed condensers of capacitance 0·0008 μF, inserted as required across the frames by a rotary switch and in parallel with a variable condenser of capacitance 0·001 μF. The output from the frames is taken to the grid of the first high-frequency valve, V_1, via the gain-control potentiometer. This consists of a combination of rheostat R_5 and potentiometer R_6, the former giving attenuation of the order of 0–15 db. whilst 15–40 db. is obtained on the latter. Tuned anode coupling is employed for the first two high-frequency valves and consists of two 0·33-H coils mounted astatically in a copper can and tuned by a 0·0013-μF condenser. Grid bias for the first valve is obtained from a small 2-volt cell *b*, while V_2 is biased from a potentiometer R_4 across a 2-volt cell which also feeds the potentiometer from which bias to V_3 is taken.

V_1 and V_2 are 2-volt screen-grid valves having an amplification factor of 170, while V_3, in the third high-frequency stage, is a triode. This is resistance-capacitance-coupled to the detector stage, which is a power triode with its grid biased to provide anode-bend detection.

The anode of the detector is connected to the deflecting coils of the oscillograph through a low-pass filter with a cut-off frequency of about 400 cycles per sec., and an attenuation at 10 kc. of about 80 db. This prevents the passage of radio-frequency potentials to the oscillograph and consequent re-radiation to the frames which are very close to it, a point of considerable importance in view of the high gain of the set.

Decoupling is employed throughout in both grid and anode feeds; and, as an additional precaution against cross-talk, separate bias batteries are provided for each amplifier.

The Vertical Aerial

A short vertical aerial, 6 metres high, is provided outside the building. It is connected to earth through a resistance of a few megohms so as to form an aperiodic circuit. A suitable portion of the aerial voltage is taken to the grid of valve V_5 by tapping along this resistance. V_5 is a high-impedance valve with a low-impedance winding L_2 in its anode, forming the primary of transformer T. This arrangement serves to impose the tuning of the frame circuit on that of the aerial and to ensure that the output of both shall appear correctly phased at the grid of valve V_1. By variation of the value of resistance R_7 or of the coupling between L_1 and L_2, the amplitude of the current fed to the frame circuit is adjusted to be equal to that produced in the frame itself.

Test Unit

In order that the sensitivity of the equipment may be maintained constant, it is arranged to produce artificially a transient impulse of constant amplitude, and to record on the drum the amplitude of pen deflection it produces. This test unit (V, Fig. 2) is indicated in the bottom left-hand corner of Fig. 3. A 2-way mercury switch W, operated mechanically from the pendulum of the driving clock, charges condenser C_8 from the battery and discharges it through resistance R_{10}, inductance L_5, a 4-turn loop coupled to the frames, and R_9, part of the loading resistance in the aerial. The loop consists of two turns of screened twin cable mounted in a fixed position on the main framework (see L, Fig. 2), care being taken to avoid closed loops when earthing the screen. The test signal in the loop induces in the frames signals simulating the arrival of a stream of constant-amplitude atmospherics from a constant azimuth, and the current in R_9 produces a " sense " indication in the test signal, the value of R_9 being so adjusted that the voltage appearing at the grid of V_1 from the aerial circuit exactly equals that derived inductively from loop L by the R-frame circuit with the frame set in the direction of maximum pick-up.

Since the radiation from the test loop is itself directional and fixed, the test-signal record serves as a directional reference mark as well as a gain calibration.

PERIOD OF OBSERVATIONS

Following a period of preliminary testing the recorder was taken into routine use in September, 1930, and it continued to operate as a narrow-sector recorder until May, 1933. At this time information on intensity of disturbance was desired, and the instrument was used for recording a cardioid diagram until March, 1935. A short period of narrow-sector recording followed, at a lower gain than that used previously, and recording ceased in August, 1935.

The following discussion is mainly confined to the sequence 1930–33. Throughout the period the equipment was tuned to 10 kc., this frequency being chosen to ensure freedom from signal interference without the necessity for resorting to very narrow band-width.

GENERAL APPEARANCE OF RECORDS

Four typical charts are reproduced in Figs. 4A, 4B, 4C, and 4D. The record commences at the bottom of each chart, at about noon, and progresses upward at the rate of 1 line in 15 minutes, time and angle increasing from left to right. At F, at the beginning and end of each chart, is the record made by the test unit, indicating the relative amplification and width of sector over which atmospherics are accepted by the equipment and serving also as an azimuthal reference mark. Fig. 4A is typical of records obtained during the winter period. A narrow sector of disturbance will be seen throughout the 24 hours in a direction north of west, one from the west during the night, and a third from the south-west during the early morning. Fig. 4B shows the more complex character of the record during the summer, indicating sources in widely differing directions, each source being active for a few hours. Frequently during the daytime deflections are obtained all round the chart, but azimuths in which the frequencies of occurrence reach maxima can usually be determined. Occasionally, when thunderstorms are in progress near the station, charts similar to Fig. 4C are obtained, the disturbed azimuth varying steadily with time, large angular swings often occurring within a few hours. In October and November two active channels are often visible throughout the day, one to the south, and the other to the north of west (Fig. 4D), the former attaining peak amplitude during the daytime while the latter predominates at night.

Marked differences can be seen in the character of the disturbance in the various sectors. At A in Fig. 4B long strokes of the pen occur, each stroke separated from the next by an appreciable time-interval. At D, on the other hand, considerable thickening of the baseline occurs due to repeated small pen excursions, the time-interval between them being insufficient to permit appreciable paper movement. In general, a distribution of the latter type is confined to a narrow sector, while the large individual strokes are much more scattered round the chart. In analysis it is possible to recognize four different types of distribution, and while the boundary between them is somewhat arbitrary, being assessed visually, and probably varying with the person analysing the record, it is of assistance when effects of the disturbance are being considered.

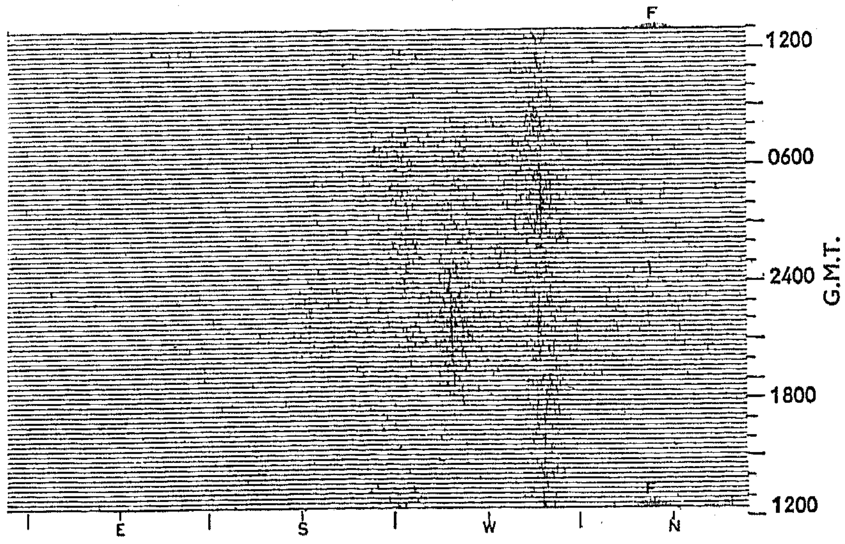

Fig. 4A.—Record for 28th–29th January, 1933.

CHARACTERISTICS OF DISTRIBUTIONS

(A) This first group consists of strokes from 4 mm. to 8 mm. in length, occurring with moderate frequency.

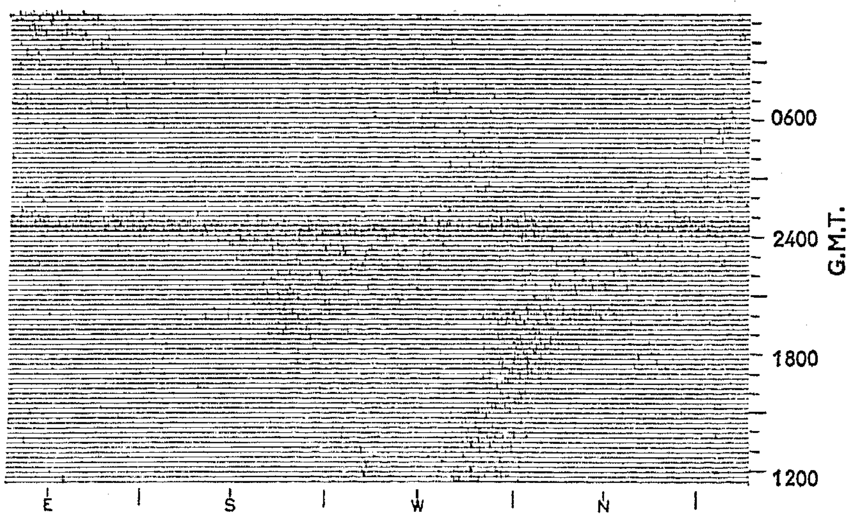

Fig. 4C.—Record for 20th–21st August, 1932.

(B) The second consists of individual strokes up to 4 mm. long occurring at a frequency at which overlapping takes place on the chart.

(C) Individual strokes up to 4 mm. long of infrequent occurrence.

(D) Overlapping individual strokes of less than 2 mm. length.

METHODS OF PRESENTATION

By placing over the original chart a transparent graticule subdivided vertically into 1-hour time divisions and horizontally into 10° steps, the disturbed azimuth and types of activity present at any hour were abstracted. This information was then carried to monthly charts, a letter for each day of the month being used and inserted in the appropriate " azimuth-hour " block indicating the hour at which a particular azimuth was disturbed. Characteristic colours for the letters were further employed to indicate the type of disturbance as outlined above. Figs. 5A and 5B show the charts for December, 1932, and August, 1931; for reproduction in monochrome the daily letter has been dropped and characteristic symbols have been adopted for the four types of distribution, namely a long line for Type A, a large dot for B, a short line for C, and a small dot for D.

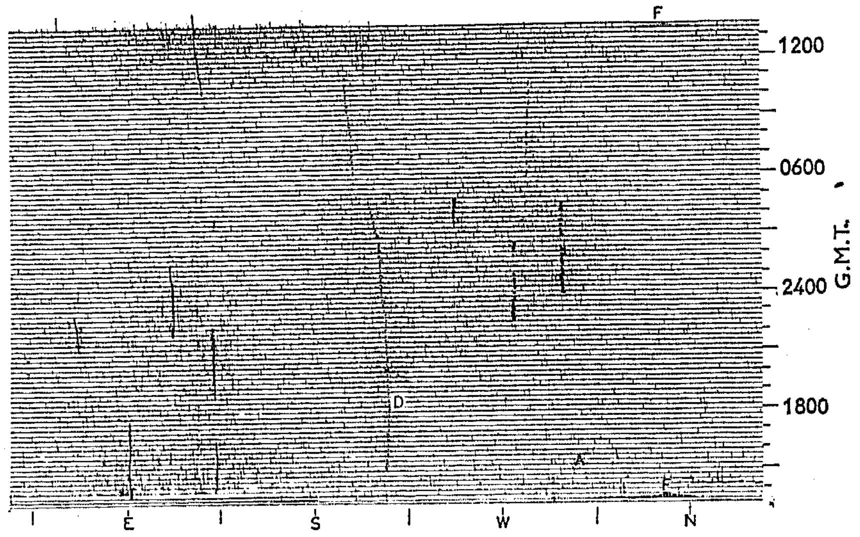

Fig. 4B.—Record for 5th–6th May, 1931.

These monthly charts have been collected into annual charts; that for the period August, 1931, to July, 1932, forms Fig. 6. Here the number of dots in a block 5° (horizontally) by 1 hour (vertically) indicate the number of days in the year on which that particular azimuth was disturbed at that hour.

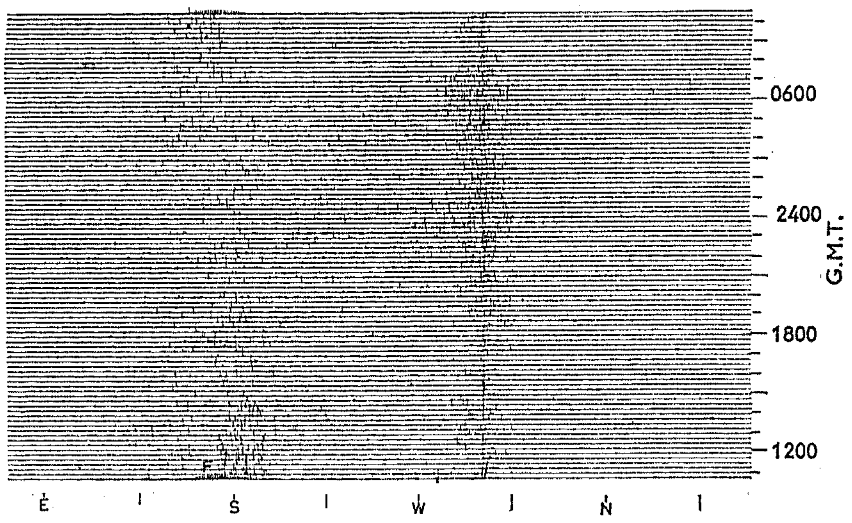

Fig. 4D.—Record for 19th–20th October, 1930.

In view of the difficulty of publishing the 12 monthly charts complete, three periods have been taken, each covering 3 hours, centred on the hours 1000, 1600, and 2400 G.M.T., these periods showing the general trend of the diurnal variation of disturbed azimuth. Curves have been prepared in which the frequency with which any azimuth is disturbed in any month is shown by the height of the curve, the frequency of disturbance being expressed as a percentage of the total number of days in the month (Fig. 7). In addition to indicating the frequency, the area below the curve has been shaded to indicate roughly the mean intensity of the disturbance from each sector. This is discussed later.

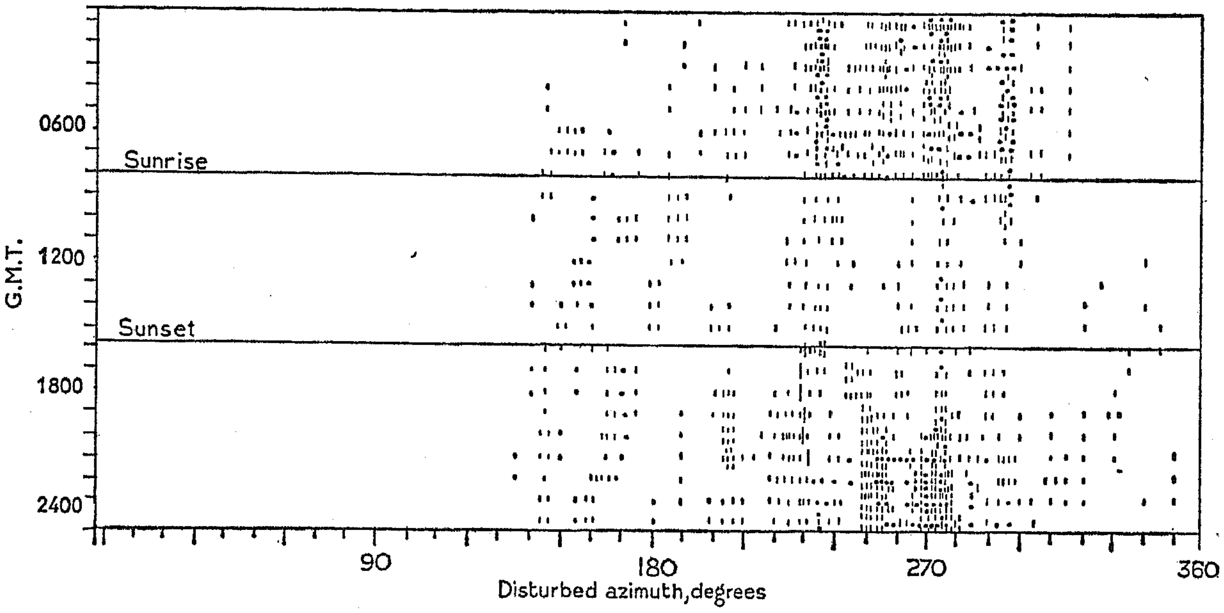

Fig. 5A.—Distribution of disturbed azimuths at each hour, December, 1932.

| Type A
• Type B
ı Type C
· Type D
Disturbance characteristics.

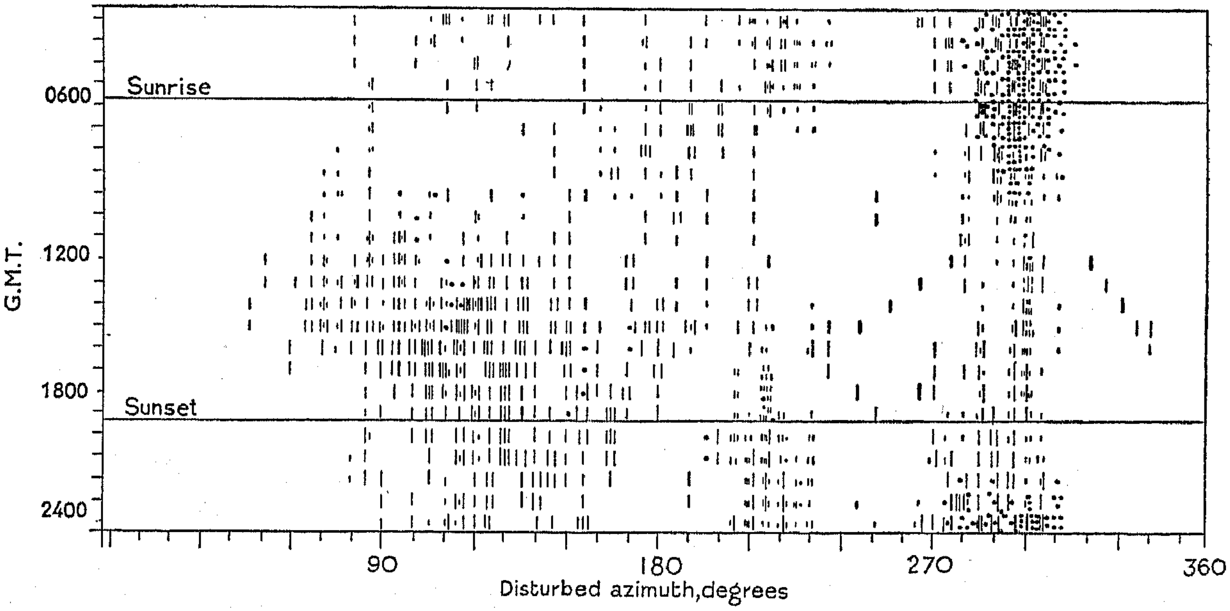

Fig. 5B.—Distribution of disturbed azimuths at each hour, August, 1931.

| Type A
• Type B
ı Type C
· Type D
Disturbance characteristics.

DISTURBED AZIMUTHS: DIURNAL AND SEASONAL VARIATIONS

Considerable variation in the disturbed azimuth occurs both diurnally and seasonally, some variations being systematic whilst others appear to be of a purely random character.

Summer

Fig. 4B shows a normal day chart, and Fig. 5B a mean monthly distribution diagram for the summer months. During the afternoon, disturbance arrives from the east and south-east and is of Type A, large individual disturbances occurring at moderate frequency. This afternoon disturbance is generally scattered over the sector 90°–200°, but the directions of peak intensity are alone plotted on the diagram. The manner in which these directions of maximum intensity vary from day to day over the quadrant will be seen in Fig. 5B. Activity commences at about 1000 G.M.T., is at its peak in the afternoon, and continues well into the evening hours.

An hour or two after sunset, sources to the west and north-west become the prominent feature. Individual disturbances are less intense than those obtained during the day, but the frequency of occurrence is much higher. The azimuth of maximum does not vary from day to day in the manner of the afternoon disturbance, nor is so wide a sector disturbed. Maxima lie between 270° and 300° during the summer. Whilst activity commences some 2 or 3 hours after sunset, it dies away at about 0700 or 0800 G.M.T., irrespective of the time of sunrise.

During the evening and throughout the night hours another active channel, at 210°–230°, is often shown. The intensity of individual disturbances is relatively small, but often the frequency of occurrence is quite high. Maximum activity in this direction occurs during April and May.

Winter

During the winter months very little disturbance arrives from the east or south-east. Occasional large individual disturbances are registered in this direction, but the most prominent source at all hours of the day lies to the west (Figs. 4A and 5A). Four distinct sectors are found, centred on 235°, 250°, 275°, and 290°. During the day activity is usually of Type C, but an hour or two after sunset the received intensity and also the frequency of occurrence increase rapidly, and a Type B distribution obtains. Maximum activity occurs at 250° and 275° during the hour around midnight, while at 235° and 290° it occurs after midnight and continues until early morning. The four centres are not often found on a single chart, and the relative amplitude of disturbance in each sector varies from day to day. On the record reproduced as Fig. 4A the sector at 290° contains the heaviest disturbance, while practically nothing is found at 270°. On this record a little activity (Type C) will be seen to the south during the evening, but this seldom attains an amplitude comparable with that from the west nor is the frequency of occurrence so high except in the months of October and November (Fig. 4D), when southerly activity is sometimes found throughout the day, with its peak in the afternoon. As summer approaches, the sources at 270°

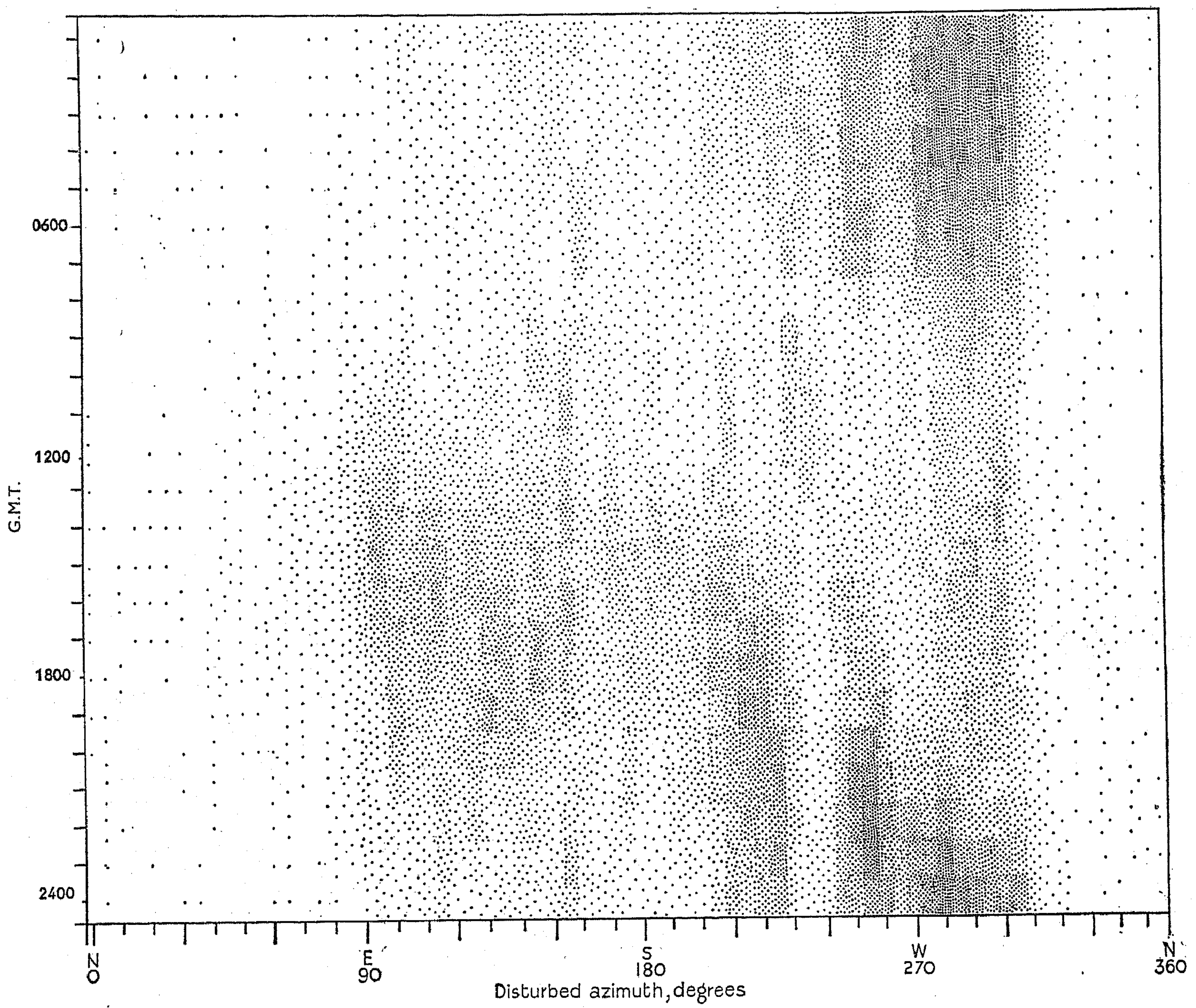

Fig. 6.—Annual distribution of disturbed azimuths at each hour.

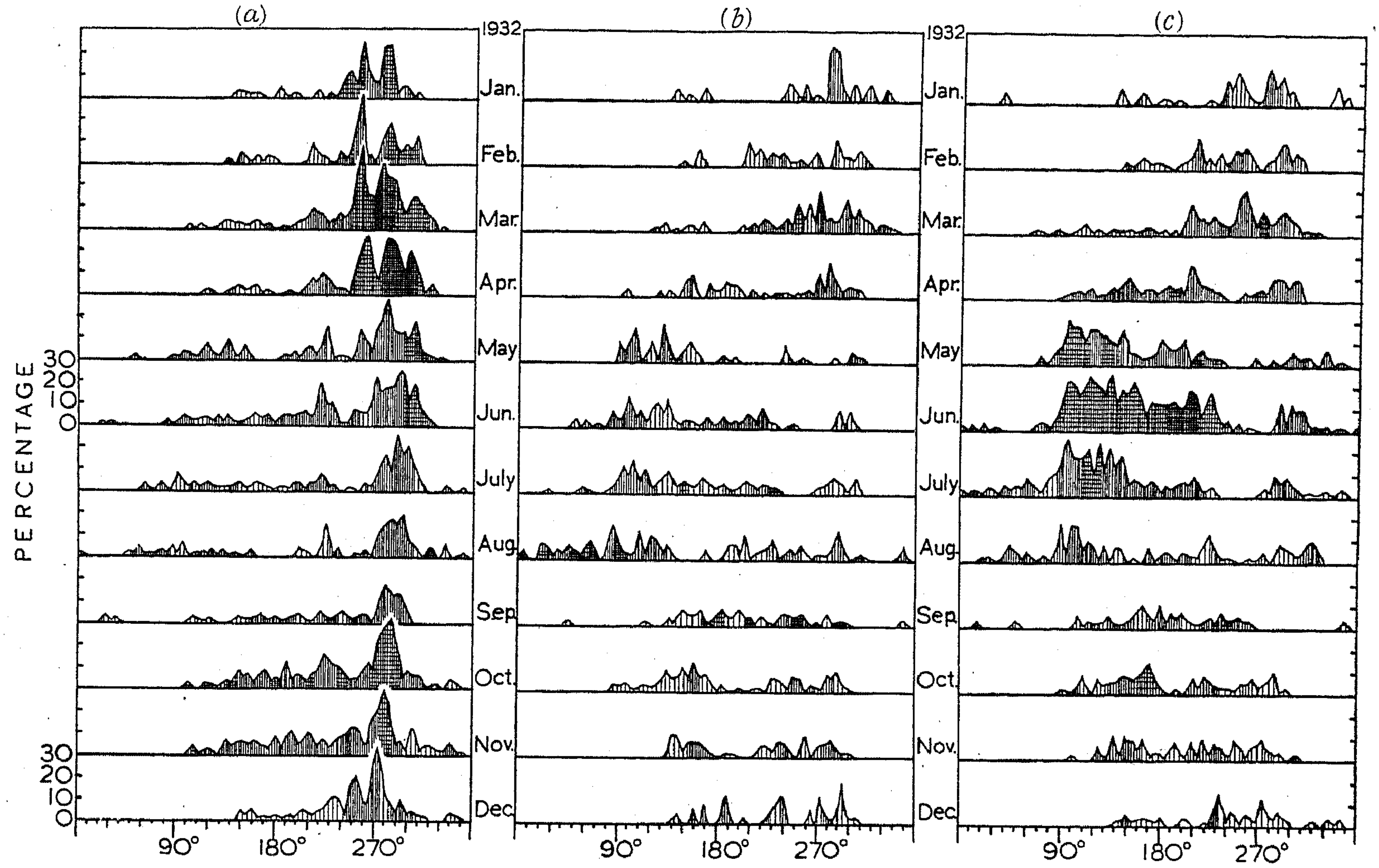

Fig. 7.—Percentage of month with disturbance at selected hours in sectors 5° wide.
(*a*) 2400 G.M.T. (*b*) 1000 G.M.T. (*c*) 1600 G.M.T.

Key to intensity shading: ▥ 1 ▥ 2 ▦ 3 ▩ 4 ■ 5

and 290° spread northward, while the sector found in December at 235° disappears and activity around 210° becomes prominent during the early evening.

The variations from month to month on these general tendencies may be seen in Fig. 7. Points which will be noted are: (1) the persistence of the westerly sources throughout the year during night hours, (2) the northerly movement of the night-time sources with the approach of summer, (3) the similarity between the azimuthal distributions in the forenoon and in the afternoon, (4) the increase of activity in these channels during the afternoon, (5) the limitation of the disturbance from south-easterly sources to the summer season.

The annual distribution diagram (Fig. 6) shows the number of occasions on which a particular azimuth was disturbed at each hour throughout the year. This number may be obtained by counting the number of individual spots in a block, 5° wide by 1 hour high. The scattered character of the afternoon disturbance and the concentration in azimuth of the night sources are clearly shown. Other points of interest which will be discussed later are: (1) the almost complete absence of activity from the northern quadrant extending from about 310° to 70°, (2) the narrow channel at 235° with very little activity, (3) the reduced activity around 265°, (4) the few occasions on which disturbance has arrived from the south.

This chart, although for one year only, may be taken as typical of those obtained for the two complete years and portions of others covered by this analysis. How closely the distribution is repeated from year to year may be gathered from the annual curves for 1931 and 1932 respectively, reproduced as Fig. 8. The general trends of the two are very similar, but minor variations will be seen in the positions of the peaks. These variations are relatively unimportant to the radio engineer, but to the geophysicist they may be of considerable interest when

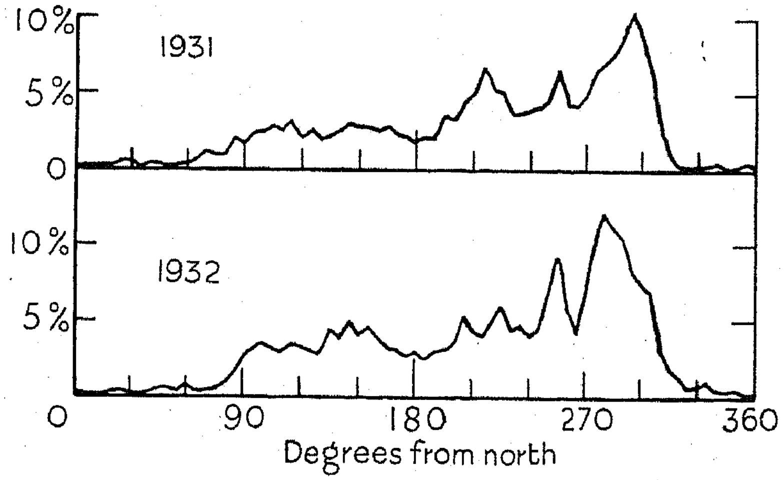

Fig. 8.—Mean annual frequency of disturbance, showing the percentage of the whole years during which disturbance was registered in any sector 5° wide.

variations from year to year in the regions of maximum thunderstorm activity and variations in propagation conditions are under consideration.

INTENSITY OF DISTURBANCE

The variation in intensity of the disturbance cannot be accurately obtained from the instrument described in this paper, for the following reasons.

Suppose the frames to be in the position to record the disturbance in the narrow sector about angle θ. If at the same instant as an atmospheric arrives along this channel a second atmospheric is received of bearing $\theta \pm (>20°)$, that atmospheric will produce a current in the opposing set and will prevent registration of the atmospheric at $\theta°$. In the limit, given two channels of disturbance 90° apart and atmospherics arriving along each with a time-interval between them shorter than the train of oscillations generated in the receivers by each, then no record would be obtained on the chart at all. Such extreme conditions have never yet been experienced in Great Britain, but it is probable that some few individual disturbances will be lost on this account and therefore too close an interpretation of intensity from records from this type of instrument must be avoided.

The provision of a switch to cut out the opposing set for alternate revolutions of the frame was at one time considered, to provide alternate lines of " cardioid " and " narrow sector " record; but, in view of the very adequate intensity analysis already covered by the earlier paper and the confusion that might arise in analysis, such a switch was never used. Some indications of the intensity of the individual disturbances which are registered may not, however, be out of place here.

The amplitude of pen deflection due to the atmospherics received over a short period was compared with the deflection obtained at the same time on the cathode-ray direction-finder,* tuned to the same wavelength, these deflections being recorded on film for detailed comparison. This apparatus had been calibrated in terms of the amplitude of a deflection produced by a steady field of measurable intensity. The large individual disturbances of Type A, appearing as a line of 6 or 7 mm., were found to correspond to a field in excess of 10 millivolts per metre, those of the second and third groups of 5 millivolts per metre, while those of the fourth represented a field of less than 1 millivolt per metre, the smallest recordable deflection being of the order of 0·25 millivolt per metre.

While the amplitudes of the individual disturbances of Type A may be quite large, to the radio engineer they may not be so troublesome as those of Types B or D because of the greater frequency of occurrence of the latter. To give some indication of the " disturbance value " at any azimuth, shading has been added to Fig. 7. This value was determined visually from the original charts by matching the number and intensity of individual disturbances obtained in a 10°-by-1-hour block on the chart against a code card, graded from 0 to 10. No. 1 of the code would be given when 5 disturbances per minute, each not exceeding 1 millivolt per metre, were registered; No. 2 would be used for 15 per minute each not greater than 1 millivolt per metre, or 3 per minute each not greater than 5 millivolts per metre; and so on, until No. 10 labelled a record completely inked over —in which neither frequency of occurrence nor individual intensity could be measured. Occasionally No. 7 of the code had to be used, indicating a frequency of some 200 per minute, many attaining at least 5 millivolts per minute. The mean hourly values for each month were used to determine the depth of shading in accordance with the key below the Figure.

SOURCES OF DISTURBANCE

From the earliest days of radio communication it has been recognized that visible lightning produces the prolonged " crashes " heard in receivers, and many workers, among the earliest being Popoff* and Fenyi,† have investigated the possibility of forecasting by radio the approach of thunderstorms. There are, however, other types of atmospherics, referred to in the literature as " grinders," " rattle," etc., appearing on our records as distributions of Types B, C, or D, the origin of which has been a matter of controversy. De Groot‡ suggested that they were produced by the bombardment of the higher regions of the atmosphere by cosmic rays, and estimated the height of the region as from 200 to 600 km. In his early work Schindelhauer§ supported this view of their origin, and when it was shown by Watson Watt,‖ in the work from which the present investigations developed, that they had marked directional properties Schindelhauer¶ introduced the effect of the earth's magnetic field, and its action in producing a spiral motion of the incoming particles, to explain these directional characteristics and their variation with time and season. Hubert,** from observations in West Africa, concluded that they were due to invisible discharges occurring at an altitude of some kilometres, at tens of kilometres from the receiver, between air masses of differing potentials, while Austin†† suggested that discharges between the meteorological cloud system over Mexico and Central America, and the electrified layers above it, produced the static of a " grinding " character heard in the U.S.A. All these explanations imply that the source of the static is local to the receiver, certainly within a few hundred kilometres. On the other hand, Bäumler‡‡ suggested that since he obtained atmospherics simultaneously from stations very far apart, the source must be at a great distance relative to that between the separate receivers. Measurements by Wilson§§ of the energy dissipated in a lightning flash showed that radiation from it could be expected to affect receivers over most of the earth, and led both Appleton and Watson Watt to conclude that tropical thunderstorm regions were probably the origin of the frequent low-amplitude atmospherics under discussion. These two workers differed, however, in their opinions as to the extent to which the visible flash could be regarded as the sole source of the atmospheric. Appleton‖‖ maintained that the origin of all atmospherics was to be found in lightning flashes, and in a recent publication¶¶ he reiterates this point of view, while the work of Watson Watt*** on locating the source by audio direction-finding at a number of stations had shown that many atmospherics originate in rain regions where no lightning flashes had been recorded by the meteorological observers. Further support was given to the theory of tropical thunderstorm origin by the short series of observations made by Round, Eckersley, Tremellen, and Lunnon* in their voyage to Australia and back. The estimate that some 100 flashes occur each second over the whole globe, made by Brooks,† and the assumption that a large number of the atmospherics generated by them would affect receivers in all parts of the world, indicate that atmospherics in sufficiently rapid succession to account for the " rattle " or " grinding " noise may reasonably be expected from such sources, and support the hypothesis of tropical thunderstorm origin, leading to an examination of the bearings of the atmospherics recorded in relation to the bearings of regions of tropical thunderstorms.

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* See References (2) and (3).

* See Reference (9).

† *Ibid.*, (10).

‡ *Ibid.*, (11).

§ *Ibid.*, (12).

‖ *Ibid.*, (13).

¶ *Ibid.*, (14).

** *Ibid.*, (15).

†† *Ibid.*, (16).

‡‡ *Ibid.*, (17).

§§ *Ibid.*, (18).

‖‖ *Ibid.*, (19).

¶¶ *Ibid.*, (20).

*** *Ibid.*, (21).

In Figs. 9A and 9B the results of the thunderstorm investigation made some years ago by Brooks have been set out on a zenithal azimuthal graticule centred on London, produced by J. St. Vincent Pletts. This map projection shows the true distance and direction from its centre of any point on the earth's surface; thus the azimuths of the several thunderstorm centres and their relative distances from the receiver are clearly presented, and the geographical nature of the paths to the receiver is easily realized. The shaded areas on the two charts show regions where storms occur on more than 20 % of the days during the periods April–September (summer) and October–March (winter). It will be seen that three active regions exist, one in the East Indies, another in Central Africa, and the third in Equatorial America, bearing 60°–80°, 140°–170°, and 210°–300° respectively. In all of these regions thunderstorms were found to occur on at least 30 % of the days of the year, and if we consider the hours of peak activity in any region to be during the late afternoon (local time) we should expect maximum disturbance to be registered here from each of the centres at about 0600–0800, 1400–1600, and 1900–2100 hours G.M.T. respectively.

To enable direct comparison to be made, curves showing the frequency with which disturbance was registered in any direction are inscribed within the boundaries of the charts. In Fig. 9A, curves for the winter periods 1930–31 (Curve *a*), 1931–32 (Curve *b*), and 1932–33 (Curve *c*), are drawn and averaged to form Curve *d*, whilst in Fig. 9B those for the summer of 1931 (Curve *a*) and the summer of 1932 (Curve *b*), with *c* as mean, are shown. Thus we may read off directly that the most frequently disturbed sector in 1931 lay on the great circle passing through the east-coast regions of North America and Mexico, and that the 5° sector centred on this azimuth was disturbed for 12 % of that summer period; the amplitude of the curve is measured radially inwards from the boundary in accordance with the associated scale indicating the percentage of the period during which atmospherics were registered in any sector 5° wide.

There can be little question that disturbance in the channel 250°–280°, the prominent feature of records during the night hours (see also Fig. 7), originates in the American thunderstorm belt. The mid-winter peaks at 255° and 275° respectively indicate sources in the north-east corner of South America and the Mexican Gulf. With the approach of the northern summer the 280° channel spreads northward to include the eastern coastal regions of North America, while the 250° South American source wanes, thus fitting closely the northward movement of the thunderstorm belt with movement of the sun to its northern solstice. These westerly sources gradually die out between about 0800 and 0900 G.M.T. irrespective of season, this being much later than one would anticipate for the cessation of storms on the American continent, but their appearance in the evening appears to lag some 2 hours behind the time of sunset, suggesting considerable control of the received amplitude by transmission conditions across the Atlantic.

The summer afternoon activity, from the east and south-east (Fig. 7), characterized by its individual disturbances of large amplitude and producing the peaks in this direction shown by the curves of Fig. 9B, undoubtedly originates in the European thunderstorm regions. The increase in April, the peak in June, and the decrease in autumn, all follow closely the increase and decrease in solar altitude over this area. The angular variations of the azimuth of peak disturbance suggest moving sources at moderate distances, and the earlier work with several recorders of the old pattern has shown how the movements of the sources may be followed by two or three recorders suitably located.* Infrequently-occurring large individual disturbances, recorded over this sector during the winter months, have their origin in the discharges which even at this season accompany the passage of cold fronts over Western Europe.

The sector 200°–220°, activity in which appears during the late afternoon and evening in most months, would include the west coastal regions of France, Spain, North Africa, and the north-east coast of South America.

Very seldom are atmospherics recorded from the sector 330°–60°. In summer, a thunderstorm centre passing over the northern part of the British Isles produces a little disturbance, but in general this freedom agrees with the paucity of thunderstorm activity in this region, as is to be expected. An occasion when disturbance occurred in this sector has already been mentioned (Fig. 4C). Here the main source was a large storm centre passing across the Midlands from west to east, while a secondary centre moved up from the south-west, passed over the receiver producing the omni-azimuthal record at about 2300–2400 G.M.T., passed away in a north-westerly direction, and died out. Contrary to expectation are (*a*) the almost complete absence of disturbance at 60°–70°, the sector including the East Indian thunderstorm region which is active during the early morning hours here; and (*b*) the few occasions on which the bearing 150°–170° reveals the rapid succession of discharges known to be occurring in Central Africa, particularly during our winter. In analysis of the records from the ambiguous recorder† it was the practice to interpret continuous disturbance recorded at 60°–100° or 240°–280° throughout the night and early-morning hours, as indicating sources to the south-west at night merging into those from the north-east in the early morning as the solar influence in the Far East became effective in thunderstorm production. It is now quite certain that nothing reaches this country from the east with intensity greater than 0·2 millivolt per metre, while from the west intensities 10 times as great are normal. It is improbable that this difference is due to varying amplitude at the source, so that the explanation must be sought in the difference in transmission conditions over the paths travelled in the two cases.

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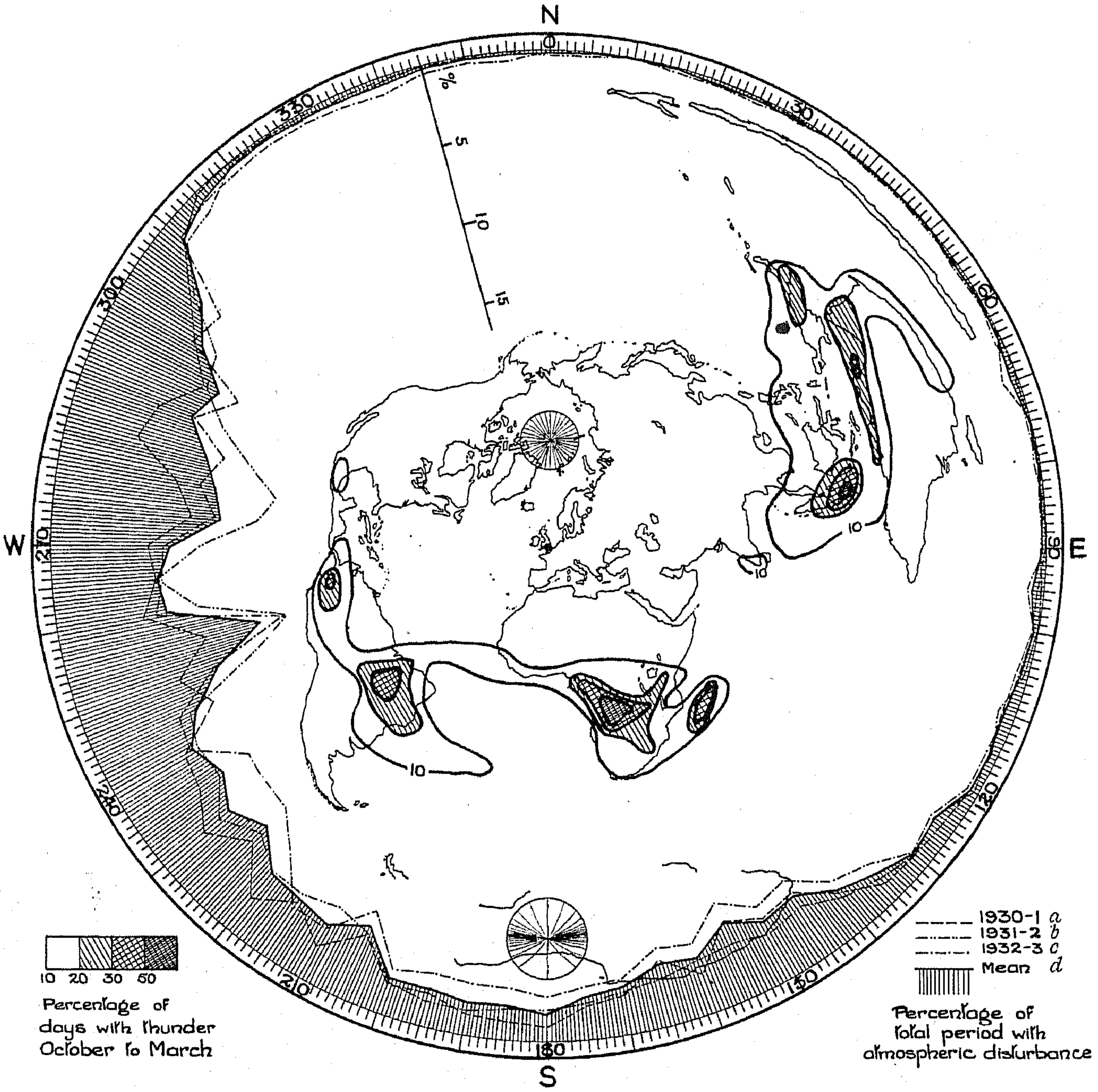
* See Reference (21).

† *Ibid.*, (4).

* See References (1), (5), and (6).

† See Reference (1).

The path to the East Indies is almost completely overland, crossing Europe, Central Asia, and Indo-China; whilst that from the West Indies and South America is almost entirely a sea path. At times when the sources are active in the east the land path is in full daylight, whilst those to the west are productive when a dark path obtains. The distances in the two cases are similar, so that if we assume comparable energy at the source the difference in received intensity, a change of at least 10 : 1, must be produced by the variation in (*a*) ground conductivity and (*b*) night-time and daytime attenuation in the medium. That (*b*) is of real significance even at these frequencies is suggested by the manner in which the westerly source is suppressed until some 2 or 3 hours after sunset.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10
10 20 30 60
Percentage of days with thunder October to March
1930-1 a
1931-2 b
1932-3 c
Mean d
Percentage of total period with atmospheric disturbance

Fig. 9A

The Central African source has also to traverse a daylight land path, with the result that while occasionally southerly disturbance has the characteristics one would expect from such a source, it never attains the intensity reached by that from the west.

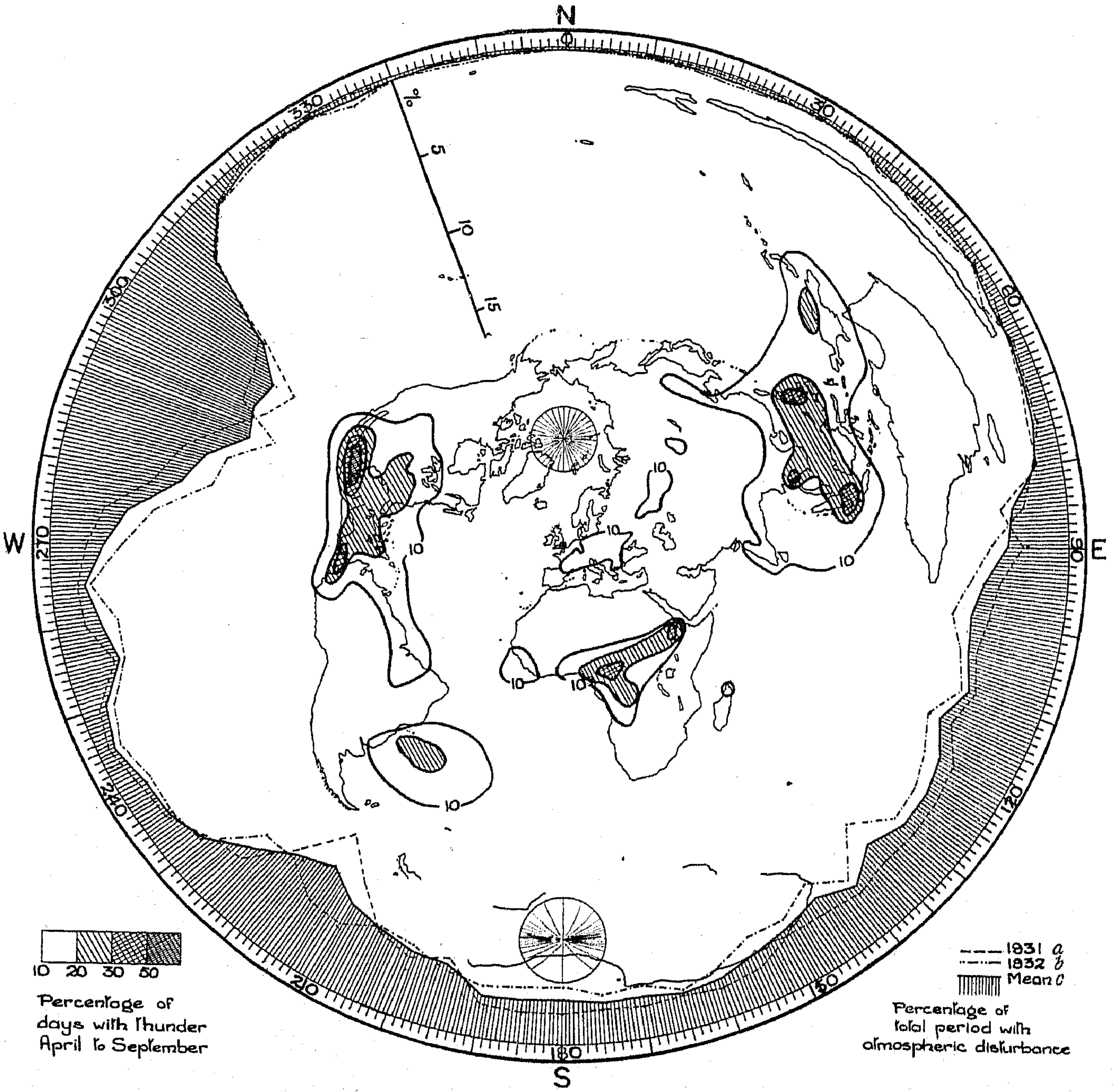
This absence of atmospheric disturbance from the East Indian and African sources has been also found by Bureau, working with a similar type of recorder in Paris in 1933 and 1934;[*] while Munro, Wark, and Higgs,[†] working in Australia, find these areas the sources of their maximum activity and obtain little disturbance from the American centres. From the geographical position of the Australian receiver there is a sea path and comparable distance to both African and American centres. Thus most of the variation in received intensity in their case is attributable to ionization conditions above the earth and not to surface conductivity.

It has been stated earlier that during the northern summer the western sources have a much more northerly origin. From this it must not be inferred that during the winter months no disturbance arrives from North

[*] See Reference (7).

[†] *Ibid.*, (8).

America. Reference to Fig. 9A shows the peak around 280° in 1931–32 to be as high as that at 250°, although from Brooks' analysis thunderstorms occur on less than 10 % of the days in the North American area. In 1930–31 and 1932–33 this peak at 280° was less prominent, and this would appear to indicate variation in the relative intensity of thunderstorm activity in these different parts of America from year to year. How accurately these curves can be used as an indication of these variations cannot be stated without day-to-day comparison with world-wide meteorology. Were the meteorological data adequate such a comparison would be economically prohibitive; but, to test how accurately the thunderstorm variations in North America are being indicated at present, a comparison was carried out for January, 1933.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10
10
10
10 20 30 50
Percentage of days with thunder April to September
1931 a
1932 b
Mean c
Percentage of total period with atmospheric disturbance

Fig. 9B

The recorder charts indicated a few hours' activity in this channel on each of the first 5 days of the month. It was then almost undisturbed until the 17th, except for 1 hour during the night of the 7th–8th and for 7 hours during the night of the 11th–12th. Considerable disturbance was then registered from the 17th until the 22nd, a quiet period from the 22nd to the 24th, and then further disturbance at night until the end of the month, with activity during the daytime also during the last 4 days.

During the early part of the month a succession of shallow depressions crossed the Northern States and Canada, with practically no evidence of associated thunderstorm activity on the Continent. The activity registered during the first few days probably originated in the squall conditions with heavy hailstorms in the Northern Atlantic at that time, a thunderstorm being reported off Nova Scotia on the 1st. The two nights with activity during the otherwise quiet period 6th–17th coincide with recorded thunderstorms near Boston on the 7th and in the Southern States on the 11th.

On the 16th a depression moved in from the Pacific, followed by a second on the 18th, and crossed the country, resulting in widespread thunderstorms in the Central States and Mississippi Valley on the 18th, 19th, and 20th–22nd, coinciding exactly with periods when atmospherics were recorded.

Two further depressions originated in the United States about the 24th, rapidly deepened, and had moved out to sea off the east coast by the 27th. There they remained stationary, still deepening, for some days, and finally filled up and passed northward at the end of the month. These were associated with widespread thunderstorms in the South-eastern States on the 24th–25th, but thereafter only one or two stations reported thunderstorms each day. The atmospheric records suggest much more intense electrical activity during the days when the associated fronts were over the Atlantic than during their travel over land; whether the discharge originating the atmospherics was visible lightning which escaped direct observation at sea, or invisible inter-cloud discharge, must remain a matter for conjecture. Very high winds were associated with this centre, reaching hurricane force over sea on the 26th and 27th. There seems little doubt, however, that the sources of the atmospherics were associated with this intense depression, and it is not without interest that during the time that it was active over sea atmospherics were received during the whole 24 hours, although during the daytime the intensity of disturbance was much less than at night.

It would appear then that the majority of the atmospherics producing disturbance in long-wave reception in this country are generated in distant regions of thunderstorm activity. They suffer variable attenuation in propagation, depending on the ionization conditions of the path along which they travel, with the result that American sources supply the majority of those with a field strength exceeding 1 millivolt per metre in England. Summer afternoon and evening sources lie in the thunderstorms of Europe, but American sources always predominate during the night and early morning.

ACKNOWLEDGMENTS

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RECENT DEVELOPMENTS IN MAGNETIC MATERIALS[*]

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SUMMARY

A review is given of recent developments in magnetic materials, including alloys for permanent magnets, " soft " materials having large initial and maximum permeabilities, and materials with constant permeability over a wide range of magnetizing force. Particular reference is made to dispersion-hardening alloys, the attainment of high degrees of purity in iron and iron alloys, improvements in sheet materials, the properties of nickel-irons, and of complex alloys based on them, after various thermal, magnetic, and mechanical treatments, and the characteristics of powdered materials.

(1) INTRODUCTION

Progress in the field of magnetic materials has in recent years been extremely rapid. Not only has the range of attainable properties both in " hard " and in " soft " materials been greatly extended, but considerable insight has been gained into the nature of the elementary magnetic particle and the physical basis of ferromagnetism.

The magnitude of the developments which have taken place in the attainable properties of magnetic materials may be realized if it is remembered that 20 years ago the hardest known magnet steel was tungsten steel, having a coercivity of approximately 80 oersteds, while the attainment by Yensen[†] under laboratory conditions of a maximum permeability of 50 000 was a striking step forward. To-day, magnet steels having coercivities 10 times as great are available commercially, and alloys with coercivities up to 4 000 oersteds have been prepared experimentally,[‡] while at the other end of the scale materials with maximum permeabilities of more than 100 000 are in common use, and a figure of 600 000[§] has been reached under special laboratory conditions of preparation.

The factors influencing the properties of ferromagnetic materials are so complex that improvements and new developments have in the past been mainly the result of empirical research, an outstanding example being the systematic investigation of the Fe-Ni-Co system of alloys at the Bell Telephone Laboratories,[||] which resulted in the discovery of the permalloy and perminvar groups. In view of the tendency to employ alloys of ternary and quaternary systems, the complete exploration of which on purely empirical lines would be an enormous task, the development of a comprehensive theory, relating the magnetic properties of a material to its composition and structure, is very desirable. Considerable progress has been made in this direction as a result of the work of Heisenberg,[†] Akulov,[‡] Becker,[§] McKeehan,[||] Bozorth,[¶] and others, while metallurgical investigations have supplied much information about the equilibrium diagrams of various systems of alloys, from which deductions regarding their probable magnetic behaviour can be made. Recently Kussmann,[**] and Ellis and Schumacher,[††] have shown how the properties of a wide range of materials may be explained on the basis of one or two general principles. The incompleteness of our theoretical knowledge is illustrated, however, by the discovery, since the publication of their papers, of alloys with exceptionally high coercivities,[‡‡] which, it is suggested, can only be explained by an extension of the principles previously enunciated. While, therefore, magnetic research may in some instances be directed along the most promising lines on theoretical and metallurgical grounds, it is not yet practicable to extrapolate far in determining the properties of materials of given composition and treatment, and progress still takes place mainly empirically.

In this paper it is proposed to describe the chief developments in the magnetic properties of both " hard " and " soft " materials during approximately the last 5 years. Earlier work, which is generally well known, will be discussed only where necessary to explain, and place in their proper perspective, more recent discoveries. In view of the empirical nature of these developments, they will be treated in relation to the magnetic properties produced and to the constitution of the materials, theoretical explanations and the technical and industrial applications of these properties being considered only incidentally.

It should be noted, however, that the vague classification of ferromagnetic substances into " hard " and " soft " materials is neither comprehensive nor precise. The materials employed in practice may be better divided into three classes, namely (i) " hard " materials suitable for permanent magnets, characterized by large remanence and large coercivity; (ii) " soft " materials of high maximum permeability and low hysteresis loss, having high remanence and low coercivity; (iii) materials of approximately constant permeability over a wide range of magnetizing forces, generally having low remanence and low coercivity.

Recently-developed materials will be grouped for discussion into these three classes.

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[*] The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

[†] See References, (1). [‡] *Ibid.*, (2). [§] *Ibid.*, (3). [||] *Ibid.*, (4).

[†] See References, (5). [‡] *Ibid.*, (6). [§] *Ibid.*, (7). [||] *Ibid.*, (8). [¶] *Ibid.*, (9). [**] *Ibid.*, (10). [††] *Ibid.*, (11). [‡‡] *Ibid.*, (2).

(2) "HARD" MAGNETIC MATERIALS

General Considerations

As already indicated, magnetic "hardness" if it is to be technically useful involves the possession of large remanence and coercivity and consequently a hysteresis loop of large area. The product of the remanence (B_R) and coercivity (H_C)* is, therefore, sometimes adopted as the criterion of the quality of magnetically-hard materials but it is more satisfactory, as suggested by Evershed,† to employ the maximum value of the product (BH) for the negative portion of the loop, i.e. the portion between the remanence and coercive-force points. This quantity, denoted by $(BH)_{max.}$, takes into account the shape of this portion of the loop and is proportional to the maximum available magnetic energy per unit volume.

The use of the term "magnetic hardness" arises from the frequent association of the characteristics so described with mechanical hardness, but it must be noted that the correlation is not complete and that an increase in magnetic may be accompanied by a decrease in mechanical hardness, and vice versa. The factors producing magnetic hardness are thus not identical with those producing mechanical hardness, although there is a close relation between them.

Various theories have been advanced to explain the origins of magnetic hardness, but it cannot be asserted that the causes producing it are yet fully known. It is well established, however, that a predominant factor is the presence of internal stresses involving distortion of the crystal lattice. Such lattice strains may be produced in a small measure by the application of external mechanical forces or by cold-working the material, but they can only be made large enough to provide the degree of hardness required in a permanent-magnet steel by introducing centres of strain on an atomic scale. Two methods of effecting this are employed in the production of the permanent-magnet materials at present available commercially, namely quench-hardening and dispersion-hardening. The precise mechanism of these two hardening processes is not yet certain, but both appear to depend on the existence of a heterogeneous structure, i.e. on the presence of at least two components or phases, one of which is dispersed in a finely-divided form throughout the matrix, causing severe lattice distortion.

Quench-hardened Steels

The two methods differ in the means adopted to obtain the dispersed phase. In quench-hardened steels its formation depends on the occurrence during cooling of a structural alteration involving a lattice-transformation in the solid state from γ-iron (face-centred cubic lattice) to α-iron (body-centred cubic lattice). By the introduction of suitable alloying constituents, e.g. C or Cr, the rate at which the transformation takes place can be greatly altered so that when the alloy is cooled rapidly from a high temperature the transformation is partly suppressed, and a structure known as martensite is produced consisting of precipitated carbide embedded in an α-lattice in such a way as to cause severe strains. All the earlier types of permanent-magnet materials, viz. carbon, tungsten, chrome, and cobalt steels, derive their hardness from a martensitic structure and thus depend on the presence of a small percentage of carbon (about 0·9 % for the maximum hardness to be developed). The properties of these steels have been summarized in various papers,* and there have been few recent developments of importance. The substitution of aluminium for cobalt has been suggested,† but no information seems to be available regarding the use of steels of this type.

The martensitic structure produced by quenching is an unstable one, and martensitic steels are therefore all liable to "ageing," although the introduction of alloying constituents additional to carbon considerably improves the stability. The structural changes producing ageing are accelerated by raising the temperature—a fact of which use is made in artificial ageing by heating to about 100° C. for some hours. This treatment produces a deterioration in hardness equal to that which would otherwise occur gradually during a period of many months. On the other hand, the deleterious effect of high temperature on the hardness is a serious limitation on the manufacturing methods that can be employed when quench-hardened steels are used, welding processes, for example, being inapplicable.

Dispersion-hardened Alloys

These disadvantages of martensitic steels are largely obviated by the use of dispersion-hardened alloys, several varieties of which, suitable for magnetic purposes, have been developed in the last five years. In these materials the formation of the dispersed phase depends on the decreasing solid solubility of some constituent with decreasing temperature. At high temperatures the alloy forms a homogeneous solid solution, but on cooling it tends to separate into a heterogeneous mixture of two kinds of crystals. By quenching from a high temperature, however, this separation can be wholly or partially suppressed and a supersaturated solution obtained. This condition is an unstable one, and by subsequent annealing at a temperature below that at which separation normally begins, the dissolved phase is precipitated in a finely-divided form. Magnetically the material is very soft after quenching, but, owing to the lattice-distortion caused by the finely dispersed precipitate, becomes hard after annealing. With prolonged annealing the hardness diminishes again, probably owing to the precipitate becoming aggregated into larger particles and causing less lattice distortion.

Dispersion-hardening can also be produced by cooling the alloy from a high temperature at a suitable rate. This method is of practical utility when the separation is not completely suppressed even by rapid cooling, and when precipitation, causing hardening, occurs in the cast alloy. Further reference will be made to this treatment later in the paper, when the Fe-Ni-Al alloys are discussed.

The heat treatment giving the best magnetic results depends naturally on the composition of the alloy and in some cases on the dimensions of the piece to be hardened, and is presumably related to the size and nature of the precipitated particles. It should be mentioned in this connection, however, that recent X-ray investigations‡ suggest that the maximum magnetic hardness may be obtained before any genuine precipitation, as indicated by variations in the lattice constant, has occurred. If the annealing is continued until clear signs of precipitation are obtained, the magnetic hardness is found to have diminished again, implying that the hardness is associated, not with actual precipitation of the second phase, but with lattice strain resulting from atomic displacements within the lattice, preparatory to the precipitation. Further, exceptionally hard alloys, which will be described in more detail later, have recently been prepared by Jellinghaus,[*] the properties of which he attributed to the development of a super-lattice, i.e. an orderly arrangement of each kind of atom within the main crystal lattice. He suggests that inter-crystalline stresses are inadequate as a complete explanation of hysteresis, and that the mutual interactions of the individual atoms must also be considered. It is evident, therefore, that our knowledge of the factors underlying magnetic hardness is still incomplete.

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* See page 308 *et seq.* for a discussion of the definition of coercivity.

† See Reference, (12).

* See References (10), (11), and (13). † *Ibid.*, (14). ‡ *Ibid.*, (15).

Types of Permanent-Magnet Alloys

(i) Binary alloys.

A large number of alloy systems have been examined during the last few years for the development of permanent-magnet properties through dispersion-hardening. Amongst binary systems no alloy displaying greater magnetic hardness than the maximum obtainable in quench-hardened steels has been discovered, as although coercive forces comparable with those of cobalt steels have been recorded[†] for an iron-tungsten alloy ($H_C = 151$ oersteds) and for an iron-molybdenum alloy ($H_C = 219$ oersteds), the values of remanence associated with these high coercive forces were low compared with those of quench-hardened steels (about 7 000 gauss). Amongst ternary and quaternary alloys, however, several groups have been found which are much harder magnetically than any previously-known magnet steel.

(ii) Iron-tungsten-cobalt and iron-molybdenum-cobalt alloys.

The first important discovery in the field of ternary alloys was made independently and almost simultaneously in 1932 by Seljesater and Rogers[†] in America and by Köster[‡] in Germany. They found that by introducing cobalt in amounts up to about 25 % the magnetic hardness of dispersion-hardened iron-tungsten and iron-molybdenum alloys could be considerably increased. Various other elements introduced as the third constituent also increased the hardness, but the influence of cobalt was particularly beneficial because it increased the saturation flux density, and hence the remanence, as well as the coercivity. Köster investigated these alloys systematically and showed that for small percentages of cobalt an almost linear increase in coercivity with increasing cobalt content is obtained.[§] The best results are obtained with alloys containing about 15 % cobalt and 10 % to 20 % molybdenum or tungsten by quenching from 1 300° C. and subsequently annealing at about 700° C. In these circumstances coercivities up to 350 and 180 oersteds can be attained in the molybdenum and tungsten alloys respectively, associated with a remanence of the order of 10 000 gauss. Köster also showed that the hysteresis loops of dispersion-hardened alloys are squarer than those of martensitic magnet steels, so that their $(BH)_{max.}$ values are larger for a given product $(B_R H_C)$. Magnetic properties equal, or even a little superior, to those of cobalt steel can thus be obtained, while the dispersion-hardened alloys have substantial advantages in their absence of ageing and the stability of their magnetic properties at temperatures up to 650° C. which follow from their metallurgical constitution, and in the possibility of working them after quenching which results from their being still unhardened. The considerable percentage of cobalt necessary, however, makes these alloys costly, and, owing to the almost simultaneous discovery of the cheaper and still harder iron-nickel-aluminium alloys, they have not been applied commercially to any appreciable extent.

(iii) Iron-nickel-copper alloys.

Another group of ternary alloys in which dispersion-hardening has been found to occur, and which is particularly interesting owing to the large variation in magnetic properties obtainable with the same composition by varying heat-treatments, is the iron-nickel-copper system. It is well known that this system includes alloys having high permeability and low coercivity, such as mumetal, but it has been shown recently by Dahl, Pfaffenberger, and Schwartz,[*] and by Neumann,[†] that it also contains a wide range of alloys which after a suitable dispersion-hardening treatment develop large coercivities reaching a maximum of about 500 oersteds at compositions in the neighbourhood of 60 % copper, 30 % nickel, and 10 % iron. The remanence is relatively low, however—only 2 000 to 3 000 gauss in the alloys having the largest coercivities—and $(BH)_{max.}$ in the best condition does not exceed $0\cdot5 \times 10^6$. Dahl, Pfaffenberger, and Schwartz found the best magnetic properties were obtained either by slow cooling from 1 050° C., or by air-cooling from 1 050° C. followed by several hours' annealing at about 650° C., but Neumann obtained substantially better results by quenching in oil from 1 000° C. and then annealing at 600° C. for 2 hours.

The outstanding advantage claimed for these alloys is that in the condition of maximum magnetic hardness their mechanical hardness is relatively small and they can be readily worked before and after their hardening treatment. Further, it has been found that cold rolling may actually improve their magnetic properties.

(iv) Iron-nickel-aluminium and iron-nickel-aluminium-cobalt alloys.

The striking magnetic properties of dispersion-hardened iron-nickel-aluminium alloys were first announced by Mishima[‡] in 1932, and have since been investigated in various laboratories. In these alloys, in accordance with the general principles of dispersion-hardening already discussed, the compound NiAl forms a solid solution with iron at high temperatures, and by suitable heat-treatment can be precipitated in a finely dispersed form. It would appear, therefore, that the ratio of the nickel to the aluminium content should be approximately the same as in the compound NiAl, and while alloys containing 10 % to 40 % nickel and 1 % to 20 % aluminium display magnetic hardness attributable to this reaction, the best results are obtained with 25 % to 30 % nickel and 10 % to 15 % aluminium, the rest being iron. Small additions of manganese, copper, chromium, tungsten, or cobalt produce slight improvements without fundamentally altering the properties of the alloys, which in their optimum state have a coercivity of 550 oersteds, a remanence of 6 000 gauss, and a $(BH)_{max.}$ value of $1 \cdot 3 \times 10^6$. Slightly higher values of either remanence or coercivity can be obtained by suitable heat-treatment, but only at the cost of a reduction in the other value and in $(BH)_{max.}$.

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[*] See Reference (2). [†] *Ibid.*, (16). [‡] *Ibid.*, (17). [§] *Ibid.*, (18).

[*] See Reference (19). [†] *Ibid.*, (20). [‡] *Ibid.*, (21).

It has been shown more recently* that the introduction of about 10 % of cobalt together with a smaller percentage of copper considerably improves the magnetic properties of the iron-nickel-aluminium alloys without materially affecting their general characteristics. In the alloys containing cobalt, a coercivity of 600 to 700 oersteds can be obtained, associated with a remanence of 7 000 to 6 000 gauss and corresponding to a $(BH)_{max.}$ value of $1 \cdot 6 \times 10^6$.

Thus, compared with the best steel previously available—35 % cobalt-steel—for which $(BH)_{max.}$ is approximately 10^6, an improvement in performance of 30 % is obtained in iron-nickel-aluminium alloys and one of 60 % in iron-nickel-aluminium-cobalt alloys. For a given performance, therefore, corresponding reductions in volume of 25 % and 40 % are possible. Since the cost of the new alloys is of the order of one-half that of cobalt steel, it is not surprising that they have almost entirely superseded the older material for use where high performance is required.

A further feature of these alloys is their relatively low density. In contrast with high-percentage cobalt-steels, which are heavier than pure iron, the iron-nickel-aluminium alloys are considerably lighter, their specific gravity being approximately 7·0. Their use thus allows a saving in weight of about 15 % to be made, as compared with cobalt-steel, in addition to that resulting from improved performance per unit volume, measured by the value of $(BH)_{max.}$. Where reduction of weight is a primary consideration, therefore, the iron-nickel-aluminium alloys are particularly applicable.

The iron-nickel-aluminium alloys differ from the iron-cobalt-molybdenum and iron-cobalt-tungsten alloys in that the precipitation of the second phase takes place very rapidly in certain temperature ranges, with the result that when cast these alloys are in general magnetically hard, and a further annealing treatment is not essential. The influence of the cooling conditions on the magnetic properties has been thoroughly investigated,† and it appears that not only are the properties of a given alloy very sensitive to the rate of cooling employed, but the optimum rate of cooling varies widely with the composition of the alloy. Within the favourable range of compositions already indicated, an increase in the aluminium content greatly reduces the rate of cooling necessary to produce the best magnetic properties. Thus Polzgüter‡ has shown that alloys of compositions approximating to 28 % nickel and 11 % aluminium give a maximum value of $(BH)_{max.}$ at a comparatively high rate of cooling, and are suitable for chill-casting. If sand-cast, they yield very low values of $(BH)_{max.}$, but by quenching the casting from about 1 200° C. values approaching the optimum values for the material can be obtained, while subsequent annealing at about 650° C. produces a further slight improvement. Alloys of compositions approximating to 25 % nickel and 15 % aluminium, on the other hand, require much slower cooling for the best results and are generally suitable for sand-casting. Since, however, the rate of cooling differs at different points in the casting, increased homogeneity, as well as improved magnetic properties in many cases, can be obtained by heating the casting to about 1 200° C. and cooling slowly to 650° C.

It is evident that, as the rate of cooling depends on the thickness of the casting, the composition of the alloy must be selected in relation to the dimensions of the casting, as well as in relation to the method of casting adopted, if the optimum magnetic properties are to be obtained. Thus, under similar casting conditions a higher aluminium content is desirable for thick castings than for thin ones.

Summarizing, it may be said that for a given composition the properties obtained in the cast state with the most favourable rate of cooling cannot be excelled by applying other heat-treatments, but, owing to the difficulty of securing the most favourable cooling conditions throughout a casting, in practice considerable improvement is usually effected by heating the casting to a high temperature (about 1 200° C.) and cooling more or less rapidly according to the composition of the alloy. The introduction of a small percentage of copper, however, with a corresponding reduction in the nickel content, renders the magnetic properties less sensitive to heat treatment and thus allows greater uniformity to be obtained.

The iron-nickel-aluminium alloys are extremely difficult to work owing to their great hardness and brittleness. They are therefore almost invariably cast in the required shape and, if necessary, ground to size. This involves the adoption of comparatively simple shapes, and, together with the fact that the molten alloy is difficult to pour, originally imposed severe limitations on the forms in which the material could be used. With improved manufacturing technique, however, these restrictions have been appreciably relaxed and more complicated forms of magnet can be made successfully.

An alternative method of employing iron-nickel-aluminium alloys* is in the form of a powder, compressed in dies with bakelite or shellac as a binding medium and then heated to a moderate temperature to fuse the binder. By this means the material may be obtained in shapes not suitable for casting. The coercivity is only 5 % to 10 % less than in the solid alloy, but the remanence is reduced by about 40 % owing to the effect of the gaps between the particles. On the other hand, the density of the powdered material is also much less and its performance, weight for weight, is thus little inferior to that of a solid magnet of the same alloy.

Like the dispersion-hardened iron-cobalt-molybdenum and iron-cobalt-tungsten alloys, the iron-nickel-aluminium alloys are free, as a result of their metallurgical constitution, from ageing effects such as occur in martensitic steels, and are also very stable in their magnetic properties when subjected to high temperatures or to mechanical shock. Thus they are weakened by only a few per cent by annealing at 500° C., and only deteriorate seriously on exposure to a temperature of 650° C. They are virtually unaffected by heating to 250° C.—a treatment which approximately halves the performance of the best cobalt-steels. It is thus possible to apply manufacturing processes involving high-temperature treatment, e.g. welding, to dispersion-hardened alloys after hardening without serious injury to their magnetic properties, and this possibility provides a useful extension of the practical range of application of permanent-magnet materials.

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* See Reference (22). † *Ibid.*, (23) and (24). ‡ *Ibid.*, (24).

* See References (10), (24), and (25).

Table 1

PROPERTIES OF HARD MAGNETIC MATERIALS

Material	Coercivity, $_JH_C$ (oersteds)	Remanence, B_R (gauss)	$(BH)_{max.} \times 10^{-6}$	Length/Diameter of straight rod for best performance
Carbon steel (1·2 % C)	60	8 000	0·18	40
Chrome steel (2 % Cr, 1 % C)	60	9 500	0·24	30
(6 % Cr, 1 % C)	70	9 500	0·28	—
Tungsten steel (6 % W, 0·6 % C)	60	11 000	0·28	25
(6 % W, 0·9 % C)	80	10 000	0·34	—
Cobalt-chrome steel (9 % Co, 9 % Cr)	150	8 500	0·55	16
(15 % Co, 10 % Cr)	200	9 000	0·7	12
Cobalt steel (35 % Co)	260	9 500	1·05	9
Iron-cobalt-tungsten alloy	150	11 500	0·8	—
Iron-cobalt-molybdenum alloy	300	10 000	1·25	—
Iron-nickel-copper alloy (18–20–62 %)	450	3 000	0·46	—
Iron-nickel-aluminium alloy	550	6 000	1·3	3·5
(Powdered)	550	3 500	0·6	—
Iron-nickel-aluminium-cobalt alloy	600	7 000	1·6	3
Oxide magnets (Kato and Takei's figures)	600	4 000	1·3	—
Iron-nickel-cobalt-titanium alloy (New KS)	900	6 000	2·1	2
Iron-neodymium alloy	4 300	800	0·15	—
Silver-manganese-aluminium alloy (87 9–4%)	5 500	500	0·06	—
Iron-platinum (78 % Pt)	1 800	4 000	2·0	—
Cobalt-platinum (77 % Pt)	4 000	3 000	2·5	—

The differences between the magnetic characteristics of the iron-nickel-aluminium alloys and the older magnet steels involve modifications in the design of permanent magnets. Without discussing the details of this question, which in individual cases are often complicated, it may be pointed out that the increased coercivity and lower remanence of the newer materials allow a shorter length of magnet while necessitating a greater cross-section in order to maintain a given flux in a gap of fixed dimensions. The influence of the properties of the material on the proportions of the most efficient magnet is indicated by the figures given in the last column of Table 1, which show approximately the optimum ratio of length to diameter for a cylindrical bar of several representative materials.

A point of importance in the treatment of these alloys with very large coercivities is the application of a sufficiently large magnetizing force to saturate the material and to produce the maximum values of remanence and coercive force. Mishima* in his original paper stated that a force of 20 000 to 30 000 oersteds was necessary for this purpose, but subsequent measurements have shown that practical saturation is reached in a field of 5 000 oersteds. Even this field strength is difficult to apply without the use of special methods of magnetization. One method that has been suggested† consists in the superposition of direct and alternating fields, a steady field of 2 000 oersteds combined with an alternating field of 1 000 oersteds amplitude being found sufficient to saturate alloys having a coercivity of 500 oersteds. In practice, magnets made of these materials are generally magnetized by means of a single copper conductor of large cross-section through which a transient current of several thousand amperes is passed by means of a d.c. surge transformer.

(v) Iron-nickel-cobalt-titanium alloys.

A series of alloys, of still larger coercivity than the iron-nickel-aluminium alloys and suitable for permanent magnets, has been prepared by Honda, Masumoto, and Shirakawa,‡ containing 15 % to 36 % cobalt, 10 % to 25 % nickel, and 8 % to 25 % titanium, the rest being iron. These alloys, known as "New KS magnetic alloys," yield coercivities up to 900 oersteds with a remanence of 6 000 gauss and $(BH)_{max.}$ values slightly greater than 2×10^6. The best magnetic properties are obtained with compositions in the neighbourhood of 30 %

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* See Reference (21). † *Ibid.*, (26). ‡ *Ibid.*, (27).

cobalt, 16 % nickel, and 12 % titanium, and it is stated that a further improvement is obtained by the addition of a small percentage of aluminium.

These alloys, like those previously discussed, are dispersion-hardening. They are not forgeable and are obtained in the best condition for use as permanent magnets by casting in metal moulds and then annealing at 660° C. for 3 hours. The remanence and coercivity of these alloys in the cast state are comparatively low. The inventors attribute this to the alloys being too hard to be fully magnetizable by the available fields (10 000 oersteds), and suggest that if a field of the order of 100 000 oersteds were applied the cast alloy would yield still higher values of remanence and coercivity. This theory, however, does not seem to have received experimental confirmation.

The New KS alloys are very stable in their properties when subjected to high temperatures (up to 650° C.) or to severe mechanical shock. Their density is relatively low—approximately 7·3. In spite of their high magnetic performance, their composition renders them expensive to produce, and the cost per unit of energy stored is greater than for iron-nickel-aluminium alloys. They are thus primarily of scientific interest, and do not appear likely to receive much commercial application.

(vi) Oxide magnets.

A permanent-magnet material, which when first described was of an entirely new type but which resembles in structure the powdered iron-nickel-aluminium materials developed subsequently and described above, is provided by the powdered metallic oxides due to Kato and Takei.* These are prepared by mixing equal quantities of powdered iron oxide (Fe_3O_4) and cobalt ferrite ($CoFe_2O_4$), compressing the mixture into the desired form of magnet, and then heating to 1 000° C. It is stated that for the best results the first magnetization should be carried out at 300° C. and the material cooled in the field. A coercivity of 600 oersteds may be obtained, but the remanence is comparatively low—about 4 000 gauss. The hysteresis loop published by the inventors is exceptionally square and the value of $(BH)_{max.}$ is therefore relatively large—approximately $1 \cdot 3 \times 10^6$. Like the powdered iron-nickel-aluminium materials, oxide magnets have a density of about 4—approximately half that of solid magnet materials—and their magnetic performance on a basis of equal weights should thus be at least as good as the best obtainable from the more usual types of material.

Jellinghaus,† however, has investigated similar powdered mixtures and, while confirming the coercivities recorded by Kato and Takei, fails to obtain values of remanence greater than 1 000 gauss. He also advances theoretical considerations, based on the composition of the powders and the magnetic properties of their constituents, showing that the values of remanence claimed by Kato and Takei cannot be attained and must be incorrect. While in the present incomplete state of our knowledge such a negative conclusion is difficult to establish definitely, Kato and Takei's results must be accepted with some reserve until independently confirmed.

(vii) Special alloys with very large coercivities.

A number of alloys having very large coercivities have been discovered recently, which, although unsuitable for general use as permanent-magnet materials owing to low remanence or high cost, are of considerable scientific interest.

In connection with these materials a distinction must be made in the definition of coercive force, which is relatively unimportant with respect to the materials of lower coercivity previously considered. Strictly speaking, " coercive force," H_C, should be defined as the negative magnetizing force required to reduce the intrinsic magnetization or the intensity of magnetization, J, of the material to zero. In practice, however, owing to the greater convenience of B/H than J/H curves, the coercive force is usually given as the negative magnetizing force required to reduce the flux density, B, to zero. To distinguish the two magnitudes the use of the symbols ${}_JH_C$ and ${}_BH_C$ has been suggested,* denoting respectively the coercive forces in terms of J and of H. The relation between them may be seen from Fig. 1, which shows curves of B and $(B - H)$, the latter being proportional to J, for the demagnetization portions of two hysteresis loops, one for an ordinary magnet steel and one for a material with an abnormally high coercive force and a comparatively low remanence. It is evident that ${}_JH_C$ is always greater than ${}_BH_C$ since when J, or $(B - H)$, is zero the value of B is $- {}_JH_C$. The magnitude of the difference depends on the slope of the B/H loop in the neighbourhood of the coercive-force point. The curve usually approximates to a straight line in this region, and we may write $(dH/dB)_C$ for the mean inclination to the vertical between the two coercive-force points. Then, from Fig. 1,

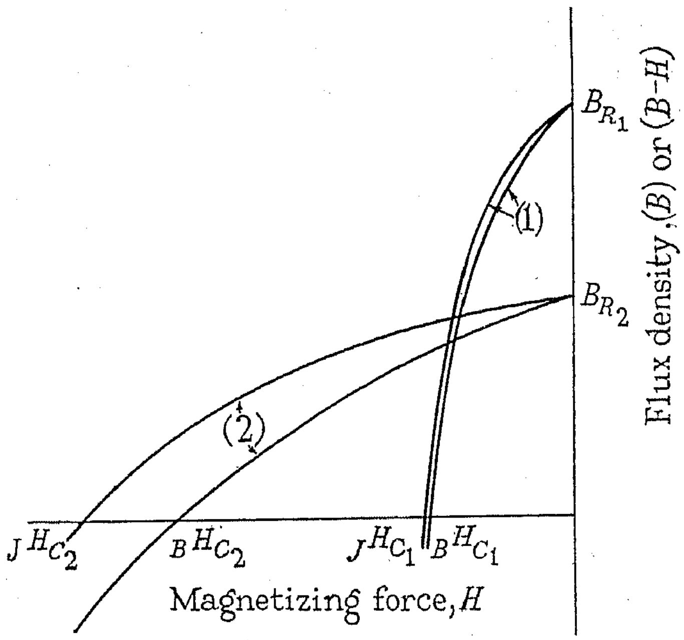

Fig. 1.—Demagnetizing curves showing relation between ${}_JH_C$ and ${}_BH_C$.

$${}_JH_C - {}_BH_C = {}_JH_C\left(\frac{dH}{dB}\right)_C$$

The difference thus increases with the coercive force and with the inclination of the curve to the vertical, which is itself related to the ratio ${}_BH_C/B_R$. Hence the difference may be expected to vary approximately as the square of the coercive force. Its rapid increase with increasing coercive force is illustrated by curves (1) and (2) of Fig. 1.

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* See Reference (28).

† *Ibid.*, (29).

* See Reference (30).

The numerical value of the difference is negligible in the older magnet steels (being less than the variation in the coercive force of nominally identical samples), and even in iron-nickel-aluminium alloys is less than 5%; but in some of the materials now to be considered, owing to the large values of ${}_JH_C/B_R$, ${}_JH_C$ may be several times greater than ${}_BH_C$. The values of coercivity given are therefore those of the theoretically correct quantity, ${}_JH_C$. The criterion of general practical utility, however, remains the value of $(BH)_{max.}$, and these materials are thus much less effective for permanent-magnet construction than the coercive-force values would suggest.

The alloys with specially high coercive forces which have so far been developed will now be briefly enumerated.

H. H. Potter,* in an examination of silver-manganese-aluminium alloys, which are analogous to the well-known Heusler alloys with silver replacing copper, found definite ferromagnetic properties with a maximum saturation intensity of magnetization, J, of approximately 70 c.g.s. units at a composition corresponding to the constitution Ag_5MnAl. He obtained coercivities up to 5 000 oersteds (${}_JH_C$), but the remanence was only about 500 gauss, and the value of $(BH)_{max.}$ may be estimated at $0\cdot06 \times 10^6$. The best properties were obtained in the cast material after annealing at 250° C. for some days, a high-temperature annealing treatment being definitely deleterious.

Drozzina and Janus† have reported that metallic neodymium containing 7 % iron (whether truly alloyed or embedded in a finely-dispersed form is not certain) is ferromagnetic and has a coercive force of about 4 300 oersteds (${}_JH_C$). The remanence, however, is only about 800 gauss.

Still more recently, coercivities of the same order, associated with relatively large remanences, have been obtained in alloys of ferromagnetic metals with platinum and palladium. Thus Graf and Kussmann‡ in a thorough study of the iron-platinum series found that alloys containing between 35 % and 65 % (atomic) of platinum were hardenable by annealing between 500° and 800° C., the maximum effect being obtained with 50 % (atomic) of each constituent, corresponding to the compound FePt. A coercivity of 1 800 oersteds (${}_JH_C$) with a remanence of about 4 000 gauss was observed. Jellinghaus§ corroborated this result in the 50 % iron-platinum alloy and observed similar, though less striking, effects in iron-palladium alloys. In cobalt-platinum alloys, however, he obtained even greater magnetic hardness, the 50 % alloy, after quenching and annealing for 3 hours, possessing a coercivity of 4 000 oersteds (${}_JH_C$) and a remanence of 3 000 gauss. He has pointed out that the (B_RH_C) product for this material is about twice as high as that of New KS steel and is the highest so far recorded, but it must be noted that its $(BH)_{max.}$ value is only of the order of 2×10^6, which is approximately the same as for the best permanent-magnet materials. All these alloys are, of course, much too costly for practical use except perhaps in special circumstances, as, for example, for the needles of moving-magnet galvanometers of high sensitivity. They are, however, of considerable interest in showing that the limits of high coercivity and of $(BH)_{max.}$ may not yet have been reached. The indications are that, for the development of sufficiently large internal strains to produce very high coercivities, the presence of a relatively large number of atoms of non-magnetic elements is necessary. This, however, involves a reduction in the attainable magnetization and hence in the remanence, which would appear to set an upper limit to the value of $(BH)_{max.}$ probably not greatly in excess of that already reached. If, however, Jellinghaus's superlattice theory, to which reference has already been made, is correct, fresh possibilities of increasing magnetic hardness are opened up, and the range of permanent-magnet properties attainable may be capable of further considerable extension.

A summary of the characteristics of representative hard magnetic materials is given in Table 1. The values given are not intended to show the utmost attainable from the various types of material but indicate what may be expected from a normal good specimen in the optimum condition. In the case particularly of the earlier materials tabulated, considerable variation in the values of H_C and B_R can be produced by variation in heat treatment without any considerable modification in $(BH)_{max.}$. As already pointed out, the coercive-force figures may be taken as either ${}_JH_C$ or ${}_BH_C$ for coercive forces up to 600 oersteds, the difference being less than the variability between different samples; at higher coercive forces the values given are for ${}_JH_C$ only.

(3) "SOFT" MAGNETIC MATERIALS

Iron and Iron-Silicon Alloys of High Purity

Magnetic hardness has been shown to be due primarily to the existence of internal stresses, which are produced most effectively by the precipitation of a component in very finely divided form. The development of exceptionally "soft" materials thus calls for the elimination of constituents liable to form such precipitates, e.g. carbon, oxygen, nitrogen, and phosphorus, the atoms of which are believed to occupy positions between the atoms in the crystal lattice, and which have, therefore, been called "interstitial impurities" in distinction from "substitutional impurities" such as nickel, copper, cobalt, and manganese, whose atoms occupy positions in the lattice.

A great deal of information on the influence of small quantities of interstitial impurities has been obtained in recent years, chiefly through the extensive investigations carried out by Yensen and Ziegler* into the properties of iron and iron-silicon alloys of high purity. Their work, besides involving the development of a special high-frequency induction vacuum furnace and of analytical methods allowing determinations of carbon and oxygen to be made to $\pm 0\cdot0005$ % and $\pm 0\cdot001$ % respectively, has included the preparation and magnetic testing of hundreds of specimens of various degrees of purity up to the highest attainable. They found that the principal constituents affecting the magnetic properties are carbon and oxygen, and succeeded in determining quantitatively the effect of each. Unfortunately the effects are not additive, while they are greatly modified by the silicon content. The results are thus complicated, and cannot in general be expressed in simple terms but only exhibited by a series of curves.

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* See Reference (31).

† *Ibid.*, (32).

‡ *Ibid.*, (33).

§ *Ibid.*, (2).

* See References (34) and (35).

A further complication arises from the influence of grain size. The importance of this factor has been widely disputed in the past, the view being held at one time that the use of large crystals would provide strikingly improved magnetic properties. Recent investigations* show, however, that in commercial materials the influence of grain size, though appreciable, is generally small compared with that of impurities, thickness, and mechanical treatment, and the properties even of single crystals are found to be not very different from those of polycrystalline materials of similar composition. In materials of very high purity, on the other hand, the effect of grain size becomes relatively important and may mask the effects of impurities unless an allowance is made for it.

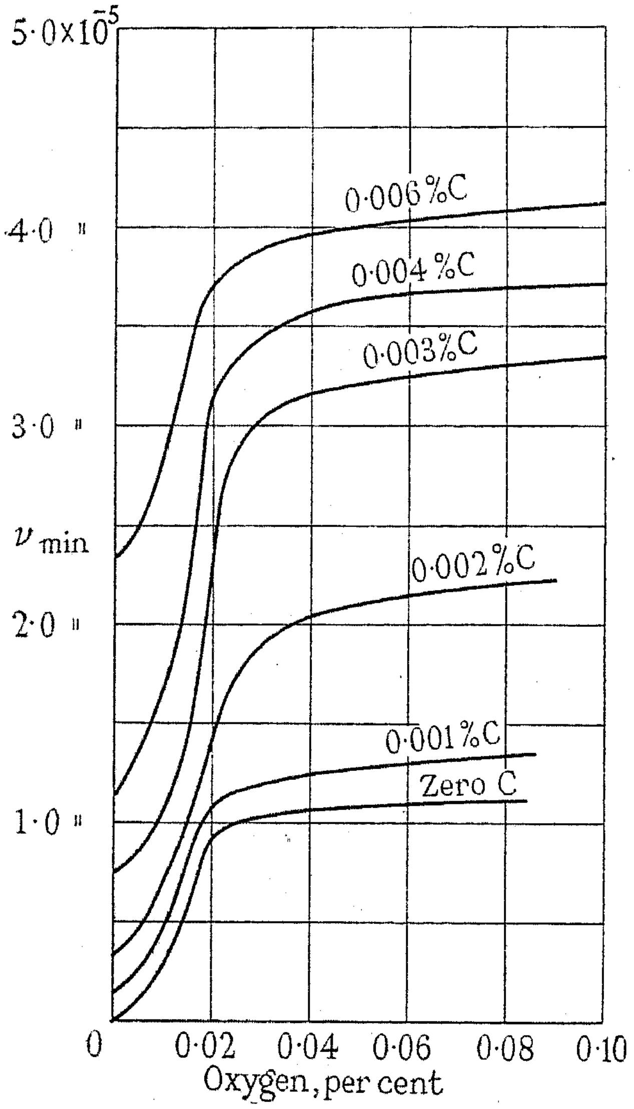

Fig. 2.—Effect of oxygen on minimum reluctivity of iron containing various percentages of carbon (Yensen and Ziegler).

The influence of impurities other than carbon and oxygen, such as manganese, phosphorus, and sulphur, had previously been determined by Yensen† and by Daeves;‡ and on the basis of these results it appeared that since in Yensen and Ziegler's series of samples the contents of these elements were very small and approximately constant, their effects could be neglected.

In expressing their results Yensen and Ziegler found that the minimum reluctivity, $\nu_{min.}$ $(= 1/\mu_{max.})$, is generally the most convenient magnetic characteristic to employ. For iron the coercive force, H_C, and the hysteresis loss, W_H, for $B_{max.} = 10\ 000$ gauss, are proportional to $\nu_{min.}$ and may therefore equally well be used, but for iron-silicon alloys the relation between the magnetic constants is not so simple, and as the coercive force and hysteresis loss become smaller relative to the minimum reluctivity as the silicon content increases, comparisons between materials with different silicon-contents give somewhat different results according to the magnetic constant considered.

It was found that, for a given composition, an approximately linear relation holds in nearly all cases between N (the number of grains per mm²) and $\nu_{min.}$ The effect of grain size may thus be eliminated by extrapolating all results to single-crystal conditions ($N = 0$).

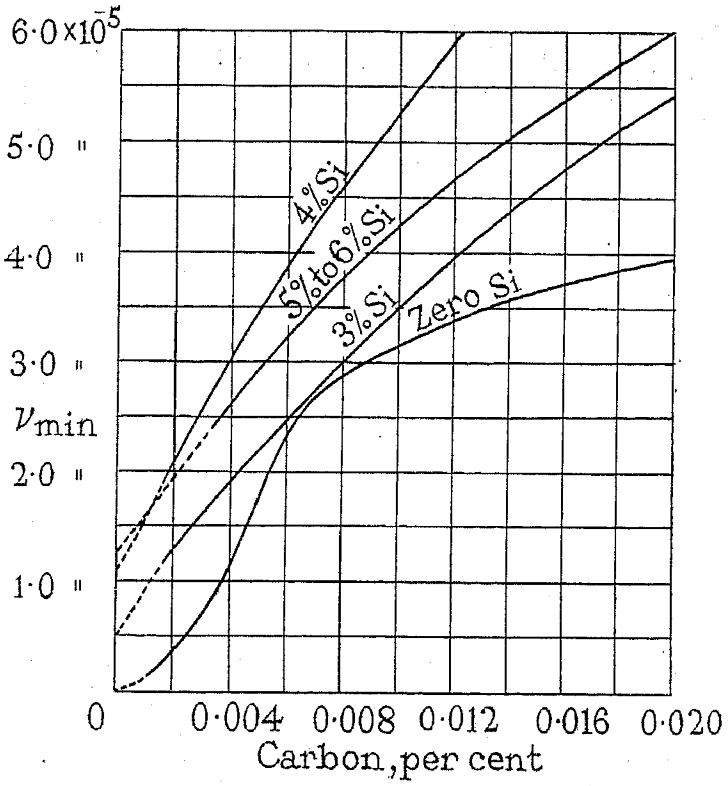

Fig. 3.—Effect of carbon on minimum reluctivity of iron and iron-silicon alloys (Yensen and Ziegler).

The effects of small percentages of impurities on the magnetic properties of single crystals are illustrated in Figs. 2 and 3. Fig. 2 shows the influence of varying oxygen-content on the minimum reluctivity of iron containing various fixed percentages of carbon. Up to a content of about 0·02 %, oxygen produces a considerable effect, but above that percentage there is little further effect. It will be noted that the alteration produced by a given percentage of oxygen is substantially affected by the amount of carbon present. In iron-silicon alloys containing 3 % or more of silicon, on the other hand, small amounts of oxygen have no appreciable effect on $\nu_{min.}$ H_C, or W_H, presumably owing to its combining with silicon to form comparatively large particles of SiO_2 which cause little lattice-distortion. (The effect of oxygen on the permeability at high field-strengths, however, is hardly altered by the presence of silicon, the introduction of 0·05 % of oxygen reducing the permeability at $H = 100$ oersteds by about 6 % for silicon-contents from 0 to 6 %.)

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* See Reference (36).
† *Ibid.*, (37).
‡ *Ibid.*, (38).

Fig. 3 shows the effect on $\nu_{min.}$ of the presence of carbon in iron-silicon alloys and in iron free from oxygen. The effect of carbon is of the order of 10 times that of oxygen in iron for small percentages, while it does not approach a definite limit as the percentage is increased, at least until much higher percentages are reached. The presence of silicon modifies the effect of carbon considerably, and apparently in a rather erratic manner. At higher percentages of carbon than are shown in Fig. 3 the curves for different silicon-contents diverge even more widely and irregularly. The reason for these divergences may lie in the form in which the carbon is present (pearlite, cementite, or graphite), which substantially modifies its effect on the magnetic properties. A further complication is thus introduced into the analysis of the results, since evidence was obtained in the investigation that the type of carbon precipitate may vary in different samples of the same composition, and that great care in heat treatment is necessary to ensure that a series of samples are in a strictly comparable and accurately reproducible condition.

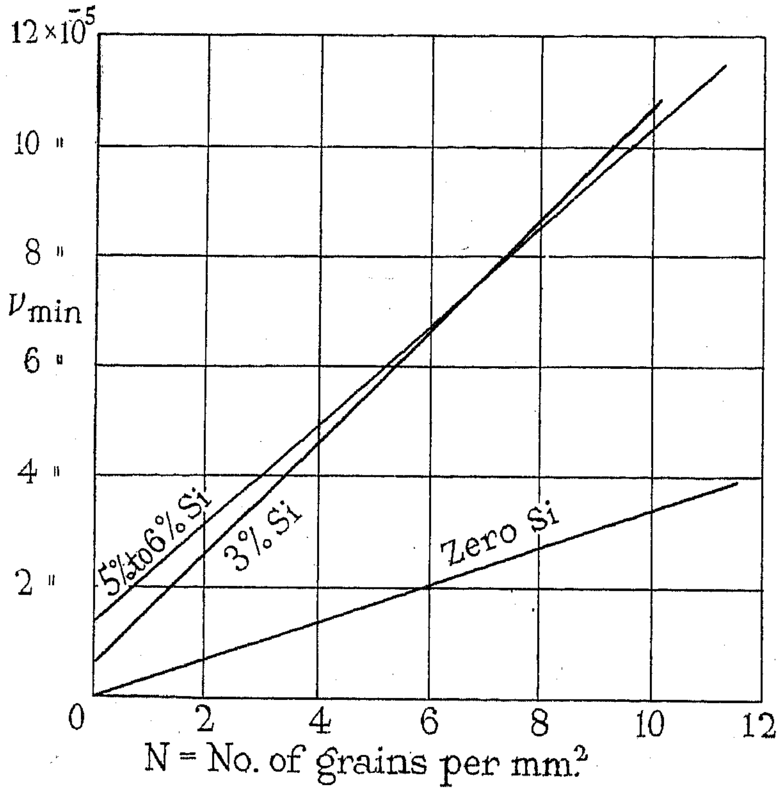

Fig. 4.—Effect of grain-size on minimum reluctivity of iron and iron-silicon alloys (Yensen and Ziegler).

It will be noticed that the curve for zero carbon in Fig. 2 and that for zero silicon and oxygen in Fig. 3 are drawn to pass through the origin, indicating an infinite permeability for a single crystal of perfectly pure iron. The highest permeability actually recorded was approximately 210 000 for a sample containing 0·001 % carbon, 0·002 % oxygen, and having 0·63 grain per mm^2, and there is some uncertainty attaching to the triple extrapolation to the ideal case. It is clear, however, that with a progressive reduction in the percentage of impurities an increase of the maximum permeability to extremely high figures is to be expected. The curves of Fig. 3 for the silicon alloys, on the other hand, do not approach zero as the carbon percentage approaches zero, indicating that silicon exerts, besides its well-known beneficial influence in reducing the effect of interstitial impurities, a deteriorating influence on the magnetic properties of pure iron.

To allow the magnitude of the effect of grain size to be compared with that of impurities, curves based on Yensen and Ziegler's results are given in Fig. 4 for iron and iron-silicon alloys of high purity showing the variation of $\nu_{min.}$ with N. It is apparent from these that grain size may be an important factor in determining the permeability of very pure materials.

Yensen and Ziegler's results have been dealt with in some detail because, although not directly of practical importance and not to be regarded as definitive, they represent an attempt to obtain fundamental data from which the properties of materials within a wide range of compositions may be deduced. Their work has shown the difficulties inherent in the synthetic derivation of magnetic properties on the basis of composition, and has provided a valuable preliminary survey of the problem for an important group of materials.

Hydrogen-treated Iron

The high permeabilities obtained by Yensen and Ziegler in pure iron have been exceeded by Cioffi[*] by means of special high-temperature hydrogen treatments. Several variations in the heat treatment were tried, but the best results have been obtained by annealing for 18 hours at 1 480° C. in hydrogen saturated with water at room temperature, cooling rapidly (in about 1 hour) to 880° C., annealing for a further 18 hours at that temperature (also in hydrogen), and then cooling slowly. By applying this treatment to Armco iron, a maximum permeability of 340 000 with an initial permeability of 20 000 and a coercivity of 0·03 oersted has been attained, as compared with values of 7 000, 250, and 0·9 oersted for the untreated iron. The precise reason for the development of these striking properties is not certain. It is known that prolonged high-temperature treatment in hydrogen is effective in removing impurities such as carbon, oxygen, nitrogen, and sulphur, and it has been suggested that the improved magnetic performance is entirely the result of this purification. It seems probable, however, that in addition to this effect hydrogen exerts a positive beneficial influence and is to be regarded as an alloying constitutent which even in small quantities increases the permeability of iron. This view is supported by the results of Adcock and Bristow,[†] who found only relatively low values of maximum permeability (15 000 to 30 000) in samples of very high purity (total impurities approximately 0·01%), for which in particular the hydrogen content was known to be small.

It is to be noted that high-temperature hydrogen treatment also produces substantial improvement in the properties of nickel-iron alloys, notably the 50 % alloy, in the commercial preparation of which a hydrogen anneal plays an important part.[‡]

Commercial Pure Iron

The treatment employed by Cioffi is too complicated for commercial application and is, moreover, difficult to render effective in samples of large cross-section. The principal methods of preparing pure iron used commercially are electrolytic deposition, vacuum melting and annealing, and the carbonyl process.

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[*] See References (39) and (4).

[†] *Ibid.*, (40).

[‡] *Ibid.*, (41).

Electrolytically-deposited iron as first obtained contains considerable hydrogen causing internal strain, and is relatively hard—its coercivity may amount to 10 oersteds—but by annealing at 900° C. and cooling slowly the hydrogen may be removed and a very soft iron produced (coercivity = 0·3 – 0·4 oersted). The properties of electrolytically-deposited sheet material will be discussed later.

Vacuum melting, owing to avoidance of gas contamination, interaction of carbon and oxygen and their removal as carbon monoxide, and simultaneous reduction in the nitrogen content, provides an appreciably purer product than previous furnace methods or than the simple electrolytic process, with consequent better magnetic properties. Vacuum annealing of iron produced by other methods also leads to substantial improvements in magnetic properties owing to the purification obtained through the occurrence of similar reactions. The effectiveness of the removal of carbon and oxygen clearly depends on the relative quantities present, the best results being secured when they are in equivalent proportions.

The carbonyl process,* developed in Germany, consists in the preparation of iron carbonyl, $Fe(CO)_5$, by the circulation of carbon monoxide over reduced iron under pressure, and its subsequent decomposition by heating to about 200° C. The iron is obtained in powdered form, consisting of spherical particles of the order of 10^{-4} cm. in diameter, but is readily converted into a solid material of equal mechanical strength with ordinary iron by heating at 1 200° C. under pressure in hydrogen. The material is exceptionally free from sulphur, phosphorus, silicon, and manganese, but in the powdered form contains up to 1 % of carbon. During the subsequent treatment, however, this carbon may be almost completely removed and a very pure iron results. The ease with which the sintering process is carried out is attributed to the small size and perfection of form of the particles and to the high degree of purity of the material. The magnetic properties of the final product are exceptionally good, its initial permeability, in particular, being over 2 000 as compared with values of a few hundreds in other commercial types of high-purity iron.

A summary of the compositions and magnetic characteristics of representative examples of various sorts of " pure " iron is given in Table 2. Pure iron, however, is rarely employed in magnetic practice as its low resistivity renders it unsuitable for a.c. applications, while high permeability and low coercivity can be obtained more easily in suitable alloys. It is chiefly used, in fact, in the preparation of such alloys, in which the quantity of interstitial impurities must be kept small although their effect is less harmful than in iron itself.

Iron-Silicon Alloys

Of the non-magnetic elements with which iron can be alloyed the most important is silicon, which provides increased resistivity combined with improved magnetic properties in weak fields, thus reducing both eddy-current and hysteresis losses under alternating magnetization. The magnetic improvement is explained by the elimination of the harmful effects of oxygen, noted in connection with Yensen and Ziegler's results, and the reduction of the effect of carbon by its conversion into the graphitic form. Moreover, silicon iron is relatively cheap to manufacture, and up to a silicon content of about 4 % possesses sufficiently good mechanical properties for the necessary constructional processes to be applied to it satisfactorily. A further advantage is the practical elimination of " ageing." As Köster's investigations* have shown that the increase in coercivity involved in ageing is a dispersion-hardening effect due to the precipitation of nitrogen from a supersaturated solution, the beneficial effect of silicon in this respect is probably due to an increased solubility of nitrogen.

Iron-silicon sheet containing 0·5 % to 4·0 % silicon is therefore almost exclusively used in electrical machine and transformer construction where an alternating or varying flux is to be carried. The use of more than about 4 % silicon is not practicable owing to the brittleness produced, but it would in any case be of little value magnetically since at this composition the

Table 2

COMPOSITION AND MAGNETIC PROPERTIES OF IRON OF HIGH PURITY

Iron	Percentage of impurities		Permeability		Coercivity H_C
	Carbon	Oxygen	Initial (μ_0)	Maximum ($\mu_{max.}$)	
Armco	0·02	0·06	250	7 000	0·8
Electrolytic	0·02	0·01	600	15 000	0·35
Carbonyl	0·005	0·005	2 000	15 000	0·2
Vacuum-melted ingot iron	0·01	0·03	—	20 000	0·35
Yensen's purest iron	0·001	0·002	—	210 000	0·035
Cioffi's hydrogen-treated iron	0·005	0·003	6 000	200 000	0·04
	—	—	20 000	340 000	0·03

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* See References (42) and (43).

* See Reference (44).

main effect of increasing the silicon content is on the resistivity, and, as the eddy-current loss in sheets of normal commercial thickness (0·3–0·5 mm.) is only a small fraction of the total loss, further increase in the resistivity has little influence on the total loss. For further improvement in magnetic performance a reduction in the hysteresis loss is required, which, as shown by Yensen and Ziegler's results, is mainly bound up with the elimination of impurities, particularly carbon. The principles and methods of purification discussed in connection with iron are largely applicable to iron-silicon alloys, and the extent to which those methods are adopted commercially is determined purely on economic grounds.

At the present time normal hot-rolled 4 % silicon sheet, 0·35 mm. thick, is given a final annealing in packs for 2–4 hours at 800°–900° C. followed by a slow cooling, and yields a maximum permeability of 8 000–10 000 with an initial permeability of 250–600, a coercivity of about 0·5 oersted, and a total power loss of 1·0–1·3 watts per kg. for a flux density, $B_{max.}$, of 10 000 gauss and a frequency of 50 cycles per sec. The trend of recent development has been towards the attainment of a more uniform product rather than any marked improvement in the magnetic properties of the best material. There has also been improvement in the mechanical properties of the sheets, notably in flatness and smoothness of finish, allowing better space factors to be obtained and reducing strain in the material when a complete core is built up.

By the use of carbonyl iron a commercial silicon-iron sheet, having appreciably better properties than the ordinary product, has been obtained, its superiority resulting directly from the greater purity of the material employed.

As in pure iron, the effect of grain size has been examined by numerous investigators and conflicting conclusions have been drawn. Thus Wimmer and Werthebach[*] found that silicon alloys of various compositions, having large grain-sizes produced by suitable combinations of cold-working and re-crystallizing annealing treatment, displayed substantial reductions (up to 40 %) in power losses which appeared to be correlated with the increases in grain size. Eilender and Oertel,[†] however, showed that the reduction in power losses was not directly related to the grain size, and it appears probable that it is due rather to the effect of the cold-working and annealing treatment in removing or redistributing the impurities or in altering the condition of the carbon present.

Independently of crystal size it is well known that the magnetic properties of an individual crystal differ substantially in different directions, particularly at high magnetizing forces (above about 10 oersteds in iron). If, therefore, all or a large majority of the crystals in a sheet can be arranged so that their directions of easiest magnetizability approximately coincide, a material will be obtained which is very anisotropic magnetically and which in the direction of easiest magnetizability possesses a substantially larger permeability than a sheet of similar composition in which the crystals are oriented at random. It is also well known that rolled silicon-sheet normally exhibits a higher permeability and lower hysteresis loss when magnetized parallel to the direction of rolling than when magnetized in the perpendicular direction, differences of about 30 % in permeability and 15 % in losses at $B = 10\,000$ gauss being usual. Recently Goss[*] has described a combination of hot and cold rolling and special heat-treatments which yields sheet of satisfactory mechanical anisotropy and larger permeability along the direction of rolling, especially at high flux densities, than ordinary hot-rolled sheet. Goss attributed the large permeability to the presence of very perfect, small crystals, apparently oriented at random as his X-ray examination gave no indication of a preferred orientation. Subsequent examinations by Sixtus,[†] using an optical method, and Bozorth,[‡] using an X-ray method, indicate, however, that there is strong preferred orientation, while confirming the perfection of the crystals, so that the magnetic characteristics are fully explained.

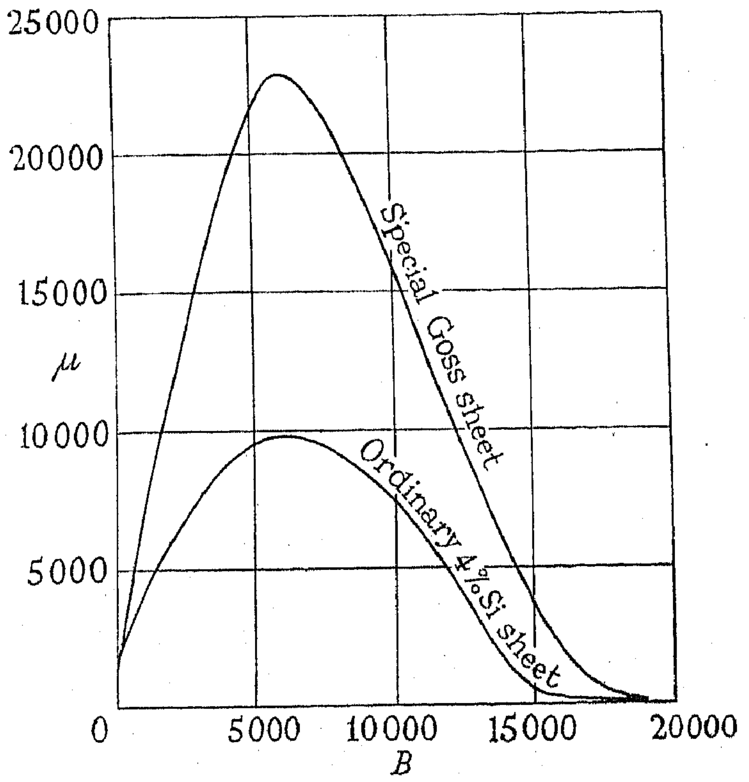

Fig. 5.—Permeability curves of ordinary and special silicon (Goss) sheet.

The treatment employed by Goss is complicated. Owing to difficulty caused by brittleness, only alloys with not more than 3·5 % of silicon are used. After hot rolling, the strip is annealed for a few minutes at about 870° C., heating and cooling being preferably rapid. It is then cold-rolled to a thickness of 0·6–1·0 mm., heated to 870°–980° C. for a few seconds, again cold-rolled to the final gauge (usually about 0·32 mm.), and given a final short annealing at about 1 100° C. The resulting sheet has a maximum permeability in the direction of rolling of about 22 000, while the total losses for $B_{max.} = 10\,000$ gauss and a frequency of 50 cycles per sec. are approximately 0·8 watt per kg. In the perpendicular direction the maximum permeability has only about one-third of this value, while at flux densities in the neighbourhood of 15 000 gauss the ratio of the permeabilities in the two directions approaches 10. The total losses for transverse magnetization are also about 50 % higher than for longitudinal magnetization. A comparison of the permeabilities of the special Goss sheet and of ordinary silicon-iron is given by the μ/B curves shown in Fig. 5. It is clear that, where the magnetic circuit can be built up so that the flux traverses the sheet parallel to the direction of rolling throughout, the special sheet gives a considerable improvement in magnetic performance compared with ordinary silicon-iron sheet.

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[*] See Reference (45).

[†] *Ibid.*, (46).

[*] See Reference (47).

[†] *Ibid.*, (48).

[‡] *Ibid.*, (49).

Other Alloy Sheet Materials

(i) Aluminium-iron and aluminium-silicon-iron.

It is well known that aluminium when introduced into iron produces very similar effects to silicon both on resistivity and on magnetic properties. While, however, the increase in resistivity is almost identical for a given content of either element, the magnetic properties of the aluminium alloys are inferior to those of the silicon alloys. Since also aluminium is a more expensive alloying material, and further the aluminium alloys are more difficult to work, they have received no practical application. Wever and Hindrichs* found, however, that small additions of aluminium to silicon-iron, especially if its silicon-content is low, produce reductions in the total losses, the effect being considerable for additions of aluminium up to about 0·5 % (the limit depending on the silicon content), but becoming negligible for further increases in aluminium content. The improvement in magnetic properties was attributed to better deoxidation and it appears that for a given silicon content, particularly in the neighbourhood of 1 % silicon, an appreciable gain is obtained by the inclusion of a small supplementary aluminium content.

More recently Masumoto,† using purer materials and larger silicon and aluminium contents, has produced ternary alloys having very large initial and maximum permeabilities and small coercivity. His investigation covered 150 alloys in the range of composition from pure iron up to about 14 % of each additional constituent, the alloys being prepared in a vacuum induction furnace and finally annealed in a vacuum at 1 000° C. for 1 hour and slowly cooled. Two regions of high permeability were found, the first in the neighbourhood of the 5·5 % silicon, 3 % aluminium alloy; the second, and more outstanding, at approximately 9·6 % silicon, 6 % aluminium. In the second region initial permeabilities up to 35 000, maximum permeabilities up to 160 000, and coercive forces—for a maximum flux density of 5 000 gauss—down to 0·02 oersted are obtained. These materials are thus very similar to the high-permeability nickel-iron alloys but have much higher resistivity. In the region of highest permeability the resistivity is about 80 microhm-cm. and this may be increased at some sacrifice of the magnetic properties by the addition of various elements, such as manganese, tin, chromium, molybdenum, arsenic, and antimony. The mechanical properties of these alloys are probably poor, but they are very suitable for use in powdered form in the manufacture of dust cores.

(ii) Beryllium-iron and beryllium-silicon iron.

An examination of beryllium-irons was carried out by Von Auwers,‡ who found, however, that the increased resistivity for a given percentage composition was less than with silicon, while the coercive force and hysteresis loss, instead of being reduced, were increased by the addition of beryllium, the increase becoming rapid above 2 % beryllium. This absence of a magnetic improvement similar to that produced by silicon is probably due to its failure to transform carbon into its less harmful forms. Like aluminium, however, in small percentages beryllium facilitates deoxidation in silicon-iron and produces a beneficial effect; but, in view of its cost, it has not been used commercially in sheet-steel manufacture.

(iii) Copper-silicon-iron.

The influence of the addition of small percentages of copper to 1·5 % and 4 % silicon-iron has also been examined* with a view to utilizing the increased resistance to corrosion obtainable in copper-irons. It was found that up to a content of about 0·7 % copper there is no appreciable effect on the magnetic, electrical, or mechanical properties of silicon-iron, but beyond this percentage a rapid increase in coercivity and diminution in maximum permeability occurs. As the maximum resistance to corrosion is obtained with about 0·5 % of copper, this quantity may be usefully introduced, where trouble from corrosion is feared, without risk of an adverse effect on the magnetic properties.

Electrolytically-prepared Sheet Material

The production of sheet material electrolytically, thus eliminating costly melting and rolling processes, with their attendant risks of the introduction of impurities, has been re-explored recently.† In unalloyed iron sheet, owing to its low resistivity the thickness must be reduced to about 0·15 mm. if the eddy-current loss is to be approximately the same as in 4 % silicon sheet of normal thickness. For sheet of this thickness total losses of about 1·1 watts per kg. are obtained at $B_{max.} = 10\,000$ gauss and a frequency of 50 cycles per sec., which is approximately the same as for ordinary silicon-iron sheet. Advantages claimed for electrolytic sheet, however, are the high permeability in strong fields and the small influence of mechanical treatment on the magnetic properties, while ageing effects are also small. On the other hand, a troublesome effect observed in this material is the occurrence of a supplementary power loss, referred to as "after-effect" loss, which reveals itself in a broadening of the hysteresis loop and a reduction in the permeability with alternating magnetization as compared with the static values. Thus, while with increasing grain-size the coercivity and hence presumably the static hysteresis loss decrease considerably to a limiting value depending on the thickness, the total losses with alternating magnetization are little affected by grain size. Since the effect occurs at frequencies much below that at which the eddy currents produce an appreciable effect, an "after-effect" loss increasing with grain size has been postulated to account for the difference between the apparent a.c. hysteresis loss and that calculated from the static loop. This difference at $B_{max.} = 10\,000$ gauss and a frequency of 50 cycles per sec. may amount to as much as 0·9 watt per kg. As a similar effect has been observed‡ in other irons of high purity, e.g. carbonyl iron, while in silicon iron it does not exceed 0·1 watt per kg. under the same conditions of magnetization, the "after-effect" loss appears to be related to the high purity or to the resulting mechanical and magnetic softness of the material. A satisfactory explanation of its origin has not yet been provided, however, although various theories have been advanced.*

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* See Reference (50). † *Ibid.*, (51). ‡ *Ibid.*, (52).

* See Reference (53). † *Ibid.*, (54). ‡ *Ibid.*, (55) and (56).

In view of the low resistivity and high after-effect loss of pure electrolytic iron, attempts were made to introduce an alloying constituent either electrolytically or by diffusion. The only material which appeared suitable for use in this way was arsenic, which could be introduced by first forming an arsenicated surface layer by heating the iron sheets with arsenic for 1–3 hours in hydrogen at 450°–600° C., and then making the arsenic diffuse uniformly through the sheets by raising the temperature to 1 000°–1 100° C. and holding it there for 4–8 hours. The effect of the arsenic content on the electrical conductivity and magnetic properties is shown in Fig. 6, and it will be seen that, in spite of a tendency for small percentages of arsenic to increase the coercivity, the conductivity and the total losses are substantially reduced by the introduction of 0·5 % to 1·0 % of arsenic. A further increase in arsenic content produces little effect on the losses but lowers the permeability at high magnetizing forces and is thus deleterious. The mechanical properties deteriorate rapidly through the addition of arsenic, the material becoming very brittle, but up to 1·3 % of arsenic they are not worse than those of ordinary transformer iron (4 % Si). Similar effects were obtained by arsenicating Armco iron and ordinary sheet iron, but not in silicon-iron, which did not allow the diffusion of the arsenic to take place. The practical utility of this process remains to be proved, but it is of interest in view of the wide departures from the ordinary methods of sheet manufacture which it involves.

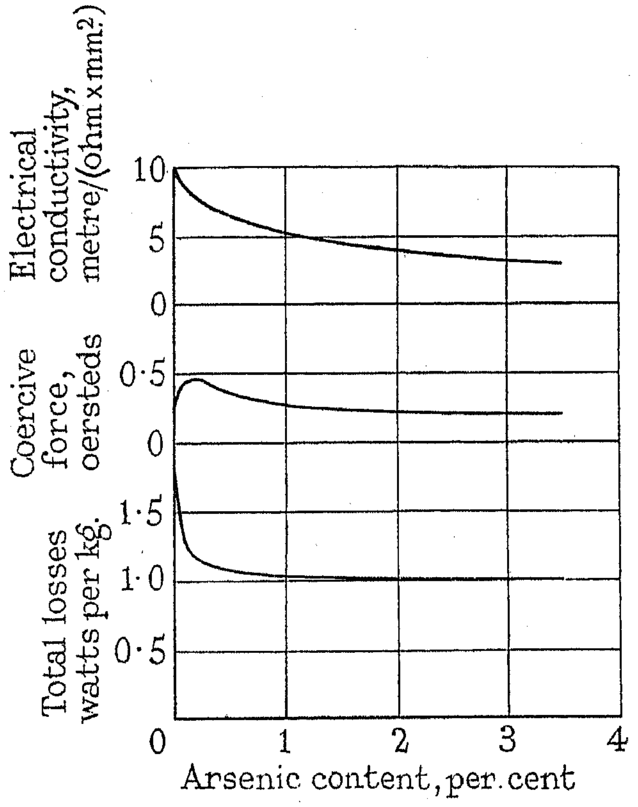

Fig. 6.—Effect of arsenic on electric and magnetic properties of iron sheet (Dahl, Pawlek, and Pfaffenberger).

Nickel-iron Alloys

The discovery of the remarkable magnetic properties obtainable under favourable conditions of purity and heat treatment in a wide range of nickel-iron alloys, and in ternary and quaternary alloy systems based on the nickel-irons, represents as striking an advance in the field of soft magnetic materials as did the development of dispersion-hardened alloys in the production of permanent-magnet materials. They have been extensively used in the loading of cables, magnetic shielding, sensitive instruments and relays, and the cores of current transformers and of choke coils and transformers for radio work, in all of which high permeability and small losses at low flux densities are required.

The fundamental characteristics of these alloys are now well known and the properties of the permalloy and mumetal types of material have been comprehensively summarized recently by Elmen* and Randall† respectively, so that only brief reference need be made to the general features underlying recent work.

The basic advance was the discovery by Arnold and Elmen‡ that nickel-iron alloys containing between 40% and 95% nickel vary greatly in their magnetic properties according to their heat treatment, the permeability in weak fields being increased and the hysteresis loss diminished when a special air-quenching treatment is substituted for the slow cooling which normally yields the best magnetic properties in other soft materials. This effect reaches its maximum magnitude in 78·5 % nickel-iron, which may be obtained with a maximum permeability of about 100 000, an initial permeability of 10 000, and a coercivity of 0·05 oersted, after a heat treatment consisting in annealing at 900°–1 000° C. and cooling slowly, then reheating to 600° C. and cooling at approximately 40 deg. C. per sec.—a rate which corresponds to cooling in air for small samples and in oil for larger samples. The same material after annealing and slow cooling has tenfold smaller permeability and tenfold greater coercivity.

As in other soft materials, interstitial impurities produce deleterious effects (though much less than in pure iron), but the values quoted can be obtained using the purest commercial grades of the constituent metals and such commercial methods of melting and heat-treatment as avoid contamination and remove oxygen and other gases satisfactorily (e.g. vacuum melting, electric furnace). While this alloy is thus much superior to previously-available commercial materials in respect of permeability at small magnetizing forces, its saturation flux density, owing to its large nickel content, is low (less than 11 000 gauss), and is reached at a magnetizing force of about 10 oersteds. Higher saturation flux densities can be obtained by using alloys containing smaller percentages of nickel (up to 16 000 gauss with 45 %–50 % nickel-iron), but in general the high-permeability nickel-irons are unsuitable if high flux densities are required. Further, when superposed d.c. and a.c. magnetizations are applied to the material, as frequently happens, for example, in radio transformers, it is important to ensure that the d.c. magnetization is not large enough to approach saturation, as otherwise the effective (incremental) permeability is extremely small even for small a.c. magnetizing forces.

Other disadvantages of the 78·5 % nickel-iron are its comparatively low resistivity (approximately 17 microhm-cm.) and the extreme sensitiveness of its magnetic properties to heat treatment and mechanical work. The use of 45 %–50 % nickel-iron largely obviates these drawbacks also, besides lowering the cost of the material, but reduces the initial and maximum permeabilities obtained to less than half those of the 78·5 % nickel alloy of equal purity. A more satisfactory method of avoiding the disadvantages of 78·5% nickel-iron is to add small percentages of one or more supplementary metals. The most important of these are copper, chromium, molybdenum, and manganese; but silicon, tungsten, vanadium, and aluminium produce similar effects. The introduction of any of these non-magnetic elements reduces the saturation flux density still further, but may substantially increase the initial permeability.

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* See Reference (57).

* See Reference (4). † *Ibid.*, (58). ‡ *Ibid.*, (59).

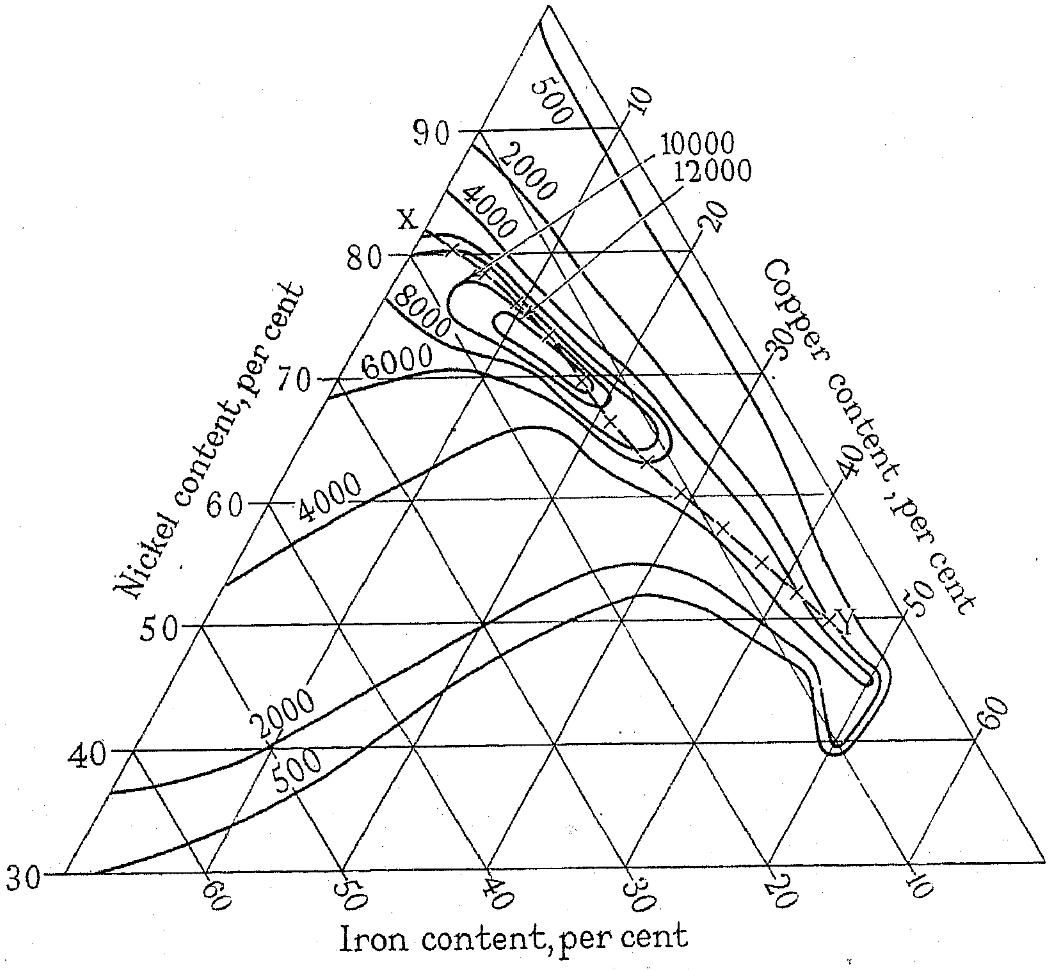

Fig. 7.—Initial permeabilities of iron-nickel-copper alloys after air-quenching (Von Auwers and Neumann).

Iron-nickel-copper Alloys

The effect of an addition of copper has been recently studied comprehensively by Von Auwers and Neumann,* who have examined alloys covering the complete iron-nickel-copper system after subjection to the following two different heat-treatments:—(1) annealing for 2 hours at 1 100° C. and cooling slowly; (2) air-quenching from 625° C. after annealing for 1 hour at 900° C. (the permalloy treatment).

The variation of initial permeability and coercivity with composition for both treatments was determined, and the existence was established of a long, narrow zone of high initial permeability and low coercivity, extending approximately from 80 % nickel, 20 % iron to 45 % nickel, 5 % iron, 50 % copper. The results of the initial-permeability measurements for the two heat-treatments are shown on the triangular diagrams of Figs. 7 and 8, in which contours are drawn connecting compositions giving equal initial permeabilities. It will be seen that the zones of optimum permeability for the two treatments are practically coincident for nickel contents below 70 % but diverge appreciably as the nickel-iron line is approached. The corresponding zones of minimum coercivity were found also practically to coincide with those of optimum permeability below 70 % nickel, but to diverge slightly at higher nickel percentages. These divergences were shown to be associated with the difference in annealing temperature between the two treatments and not with the difference in rates of cooling. A comparison of Figs. 7 and 8 shows much smaller divergences between the initial permeabilities of the ternary alloys in the optimum zone than in the binary iron-nickel alloys, indicating the influence of copper in reducing the sensitivity to heat treatment.

The influence of a comparatively small addition of copper with supplementary additions of other metals, is exemplified by the properties of mumetal (containing approximately 76 % nickel, 17 % iron, and 5 % copper), which have been fully described by Randall.* Its principal characteristics are the possession of maximum and initial permeabilities little different from those of 78·5% nickel-iron combined with a resistivity of 42 microhm-cm. and greatly reduced susceptibility to mechanical work, while the favourable magnetic properties are obtainable after a simple annealing treatment with furnace cooling.

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* See Reference (60).

* See Reference (58).

Iron-nickel-chromium and Iron-nickel-molybdenum Alloys

The addition of chromium or molybdenum is even more effective in increasing the resistivity, while in addition it produces a remarkable increase in the initial permeability, particularly after annealing and slow cooling. Fig. 9, due to Elmen,* shows the effect of increasing chromium or molybdenum content on the initial permeability of 78·5 % nickel-iron, both when annealed and when air-quenched (the nickel percentage being kept constant throughout). It will be seen that in the air-quenched alloys the initial permeability reaches a maximum value in the neighbourhood of 2 % content of either added element, followed by a substantial decrease at higher percentages. In the annealed alloys, on the other hand, a very large increase in the initial permeability is produced, reaching a sharp maximum for a content of 3·8 % of either constituent. This maximum is higher for both metals than the value for air-quenched 78·5 % nickel-iron, and for molybdenum amounts to 20 000, which is higher than the maximum obtainable in any of the air-quenched alloys.

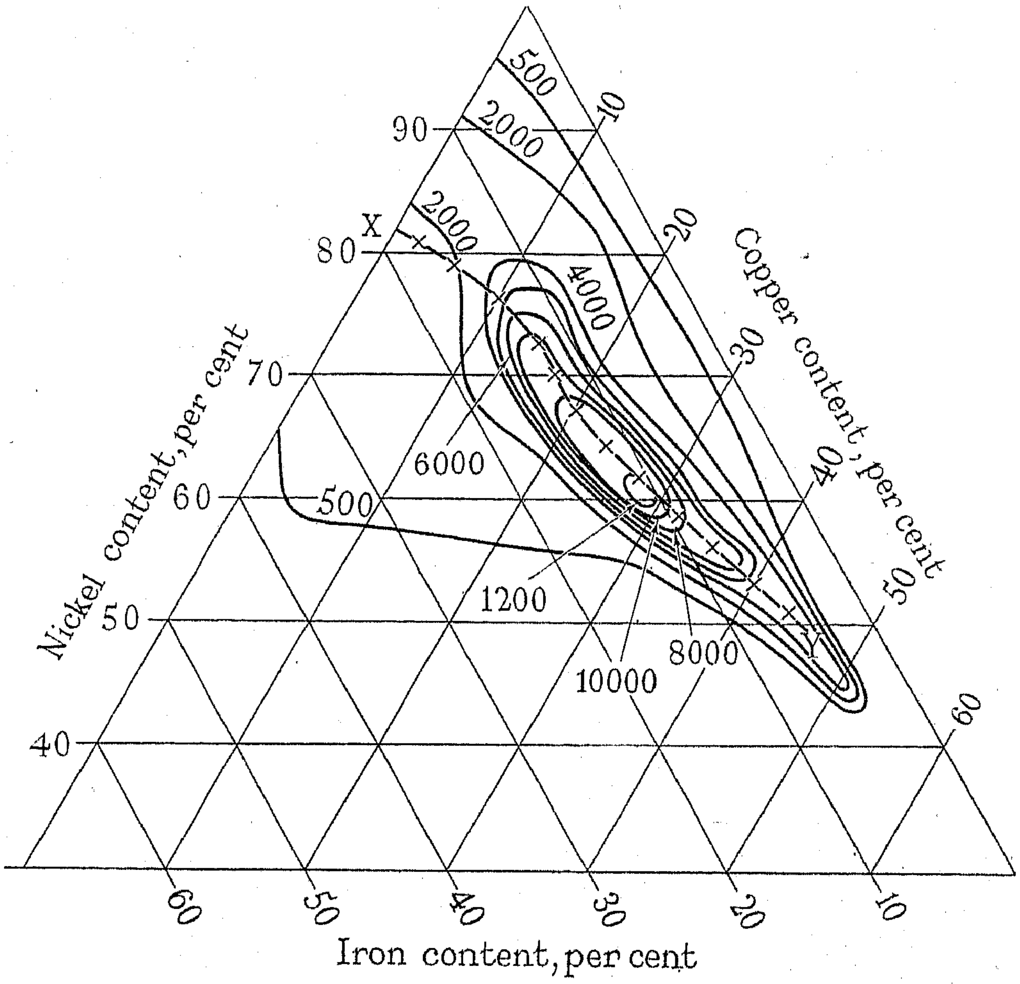

Fig. 8.—Initial permeabilities of iron-nickel-copper alloys after annealing and cooling slowly (Von Auwers and Neumann).

The alloys containing 3·8 % chromium or molybdenum have resistivities of 65 and 55 microhm-cm. respectively, and, as their high initial permeabilities are obtained after annealing and slow cooling, thus obviating the critical heat-treatment required by the binary alloy, both these alloys have been extensively employed in spite of their maximum permeabilities being 30 %–40 % less and their saturation flux densities about 20 % less than those of 78·5 % nickel-iron.

Other Ternary and Quaternary Alloys

Alloys containing 5 %–15 % manganese have also been studied* and employed commercially. They display similar characteristics to those of the alloys just described, although their permeabilities are in general lower. A small addition of manganese (0·5 %–1·0 %) is also often made to other ternary alloys to improve their mechanical properties.

The increase of initial permeability has been carried still further† in a quaternary alloy, known as "1040," for which a value of about 40 000 is claimed. Its composition (72 % nickel, 11 % iron, 14 % copper, 3 % molybdenum) indicates a high resistivity and a low saturation density, the values actually obtained being respectively 56 microhm-cm. and 6 200 gauss.

The effects of small additions of other elements on initial permeability have been described by Nishina.‡ By adding silicon the initial permeability of air-quenched 78·5 % nickel-iron is substantially increased, the maximum increase occurring with 1 % silicon. A further addition of cobalt again produces an increase in the initial permeability with a sharp maximum at 0·3 % cobalt. The effects of adding tin and titanium to iron-nickel-chromium alloys containing up to 6 % chromium were also examined, these alloys being obtainable in their optimum state after annealing. Considerable increases were obtained, reaching their maxima at approximately 3 % tin and 0·7 % titanium. These maxima were most pronounced in the alloys containing 3 % and 4 % of chromium respectively. The best results obtained were for an alloy containing 85 %

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* See Reference (4).

* See Reference (61). † *Ibid.*, (62). ‡ *Ibid.*, (63).

nickel, 10·2 % iron, 4·1 % chromium, and 0·7 % titanium; this gave an initial permeability of 15 700, a maximum permeability of about 40 000, and a resistivity of 76 microhm-cm.

An account has also been given recently[*] of the properties of a series of commercial Japanese high-permeability alloys containing, besides iron and nickel, considerable percentages of cobalt, chromium, silicon, manganese, copper, or titanium. Their properties, however, do not display any marked difference from those of the better-known commercial alloys which have been available for a number of years.

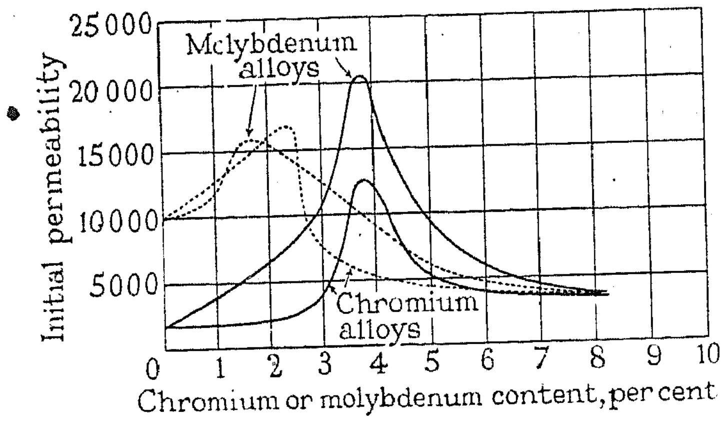

Fig. 9.—Effect of chromium or molybdenum on initial permeability of 78·5 % nickel-iron (Elmen).

------- Air-quenched.
——— Slowly cooled.

It is evident that by varying the proportions of iron and nickel, the percentage of one or more supplementary non-magnetic metal, and the heat treatment, materials with a wide range of magnetic properties and resistivity can be obtained. Permeability curves, obtained with d.c. magnetization, for some typical materials based on nickel-iron are given in Fig. 10. It must, however, be emphasized, first, that considerable variation in properties may result from small changes in heat treatment or in the amounts of interstitial impurities present, and, secondly, that with alternating magnetization the effective permeability of sheet of commercial thickness (0·35 mm.) is very much less than the d.c. value. Hughes[*] has shown recently that for a given magnetizing force the permeability at 50 cycles per sec. may be only about one-tenth of the d.c. permeability in the region of maximum permeability, and has calculated that this difference is largely explicable by the effects of eddy currents if these are assumed to depend on the differential permeability derived from the hysteresis loop rather than on the permeability at the tip-point of the loop.

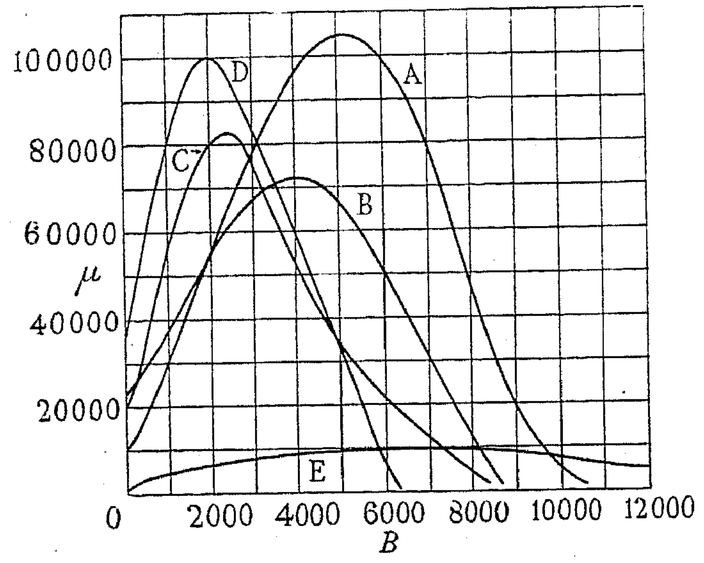

Fig. 10.—Permeability curves of high-permeability alloys.

A. 78·5 % nickel-iron. B. 3·8 % Mo, 78·5 % nickel-iron (Permalloy C). C. 5 % Cu, 76 % Ni, 17 % Fe (mumetal). D. 14 % Cu, 3 % Mo, 72 % Ni, 11 % Fe (1040 alloy). E. 4 % silicon-iron.

Effect of Crystal Orientation

As in silicon-iron sheet, a factor affecting the properties of commercial nickel-iron sheet material is the production of preferred crystal orientation by cold rolling. Wood[†] has shown by X-ray examination of mumetal that the first effect of cold rolling is lattice distortion, which increases up to about 30 % reduction and then remains constant. Preferred orientation only begins to appear at about 35% reduction, and in sheet which has been cold-rolled to more than this degree the permeability varies with the direction, being greatest in the direction of rolling. The effect is small at low flux densities but becomes considerable in the region of maximum permeability,[‡] where a substantial improvement in the properties of a magnetic circuit can therefore be obtained if the flux traverses the sheet parallel to the direction of rolling throughout. This condition is fulfilled by the use of the well-known spirally-wound cores, which, in addition, obviate the waste of material occurring with stampings.

Dahl and Pawlek,[§] on the other hand, compared the properties of sheets with and without preferred orientation (prepared by applying different degrees of cold rolling) for a wide range of compositions in the nickel-iron series, and found very small differences except in one or two samples at high magnetizing forces. Moreover, the differences observed were not always of the same sign.

Effects of Cooling in a Magnetic Field

The most striking results obtained with nickel-iron alloys, and the highest permeabilities yet recorded for any material, are those observed by Kelsall, Dillinger, and Bozorth,[||] after annealing and cooling in a magnetic field. They found that the nickel-iron alloys containing 40 %–80 % nickel, if annealed at a temperature above their Curie point and cooled slowly in a field of a few oersteds, possess much larger permeabilities in the direction of the applied field than are obtainable after the special air-quenching treatment. The maximum increase in permeability occurs at approximately 65% nickel, the actual value found depending greatly on the temperature at which the alloy is annealed. If the temperature of annealing is 1 000° C. the maximum permeability is about 250 000, but by treating in hydrogen at 1 400° C. for 18 hours and subsequently cooling in a magnetic field from 650° C. the maximum permeability is increased to 600 000 while the coercivity is reduced to 0·012 oersted. The hysteresis loops corresponding to this condition are characterized by almost vertical sides and square corners, the flux density changing practically from positive to negative saturation value for a nearly imperceptible alteration in the magnetizing force. This is illustrated by the loops shown in Fig. 11 for the 65 % nickel-iron after annealing at 1 000° C. and cooling slowly, first with no applied field and secondly with a field of 10 oersteds maintained. Owing to the enormous value of dB/dH for the steep sides of the loop, the flux-change requires a very long time (up to 3 minutes) to complete itself, while it is impossible to demagnetize the material thoroughly by reversals of a continuously diminishing amplitude. It is noteworthy that the loop is of similar shape to that obtained by applying mechanical stress to the material, and it is of interest that the magnetic properties of samples cooled in a magnetic field are much less affected by stress than those of samples cooled normally.

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[*] See Reference (64).

[*] See Reference (65).

[†] *Ibid.*, (66).

[‡] *Ibid.*, (58).

[§] *Ibid.*, (67).

[||] *Ibid.*, (68), (69), and (3).

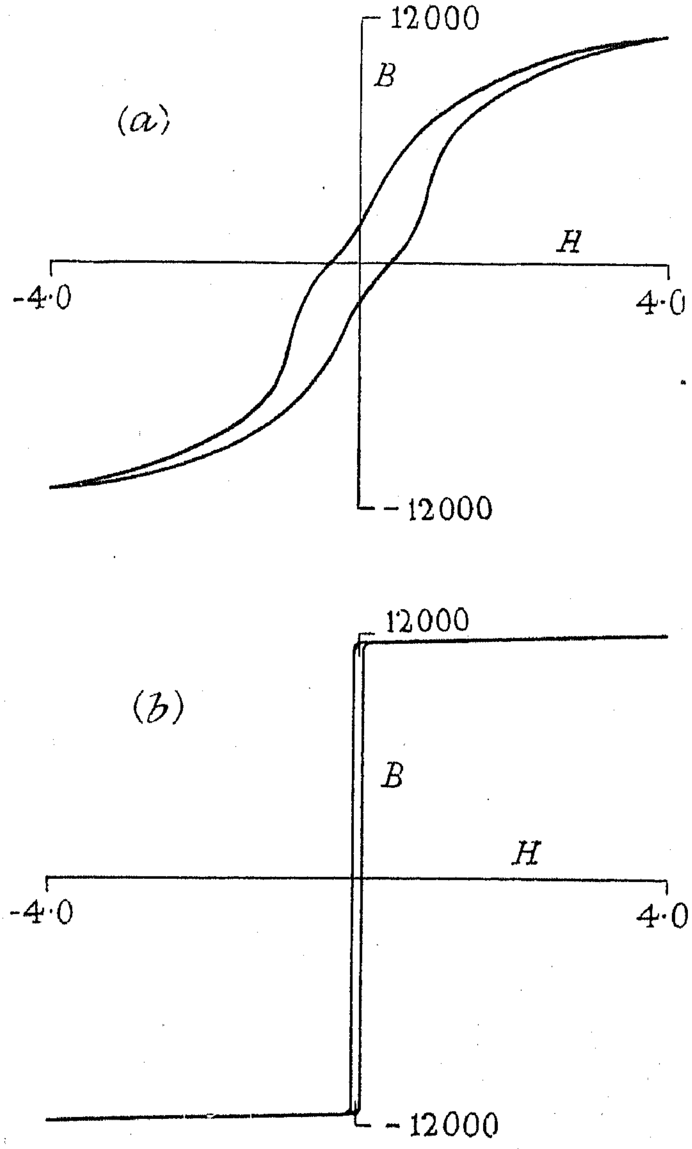

Fig. 11.—Hysteresis loops of 65 % nickel-iron cooled from 1 000° C. (Dillinger and Bozorth).

(a) No field applied during cooling.
(b) Field of 10 oersteds applied during cooling.

The increase in permeability is strongly directional, the permeability perpendicular to the field applied during cooling being generally decreased by the treatment. Similar effects to those in the nickel-irons are also produced in a wide range of iron-nickel-cobalt alloys (" perminvars "), which are discussed further in the next section, and in these even greater magnetic anisotropy has been observed, a ratio of 150:1 between the maximum permeabilities parallel and perpendicular to the applied field being measured in one sample containing 30 % iron, 25 % cobalt, and 45 % nickel.

Dahl and Pawlek* confirmed the large effect of cooling in a magnetic field in nickel-iron and nickel-iron-cobalt alloys, both with and without preferred orientation, and looked for a similar effect in iron and in certain iron-silicon and iron-cobalt alloys. In these materials, however, the changes in magnetic properties produced were found to be small.

A detailed investigation† established that the effect depends on the application of the field at a temperature below the Curie point and above about 400° C., which is approximately the lowest temperature at which plastic flow occurs. The theory, suggested by this result, that the effect of the applied field depends on plastic flow, is supported by a study of the rates at which magnetic changes take place at these temperatures; these are found to follow the same laws as other phenomena known to be due to plastic flow.

Theories of Behaviour of Nickel-Iron Alloys

Various theories have been put forward to account for the magnetic characteristics of nickel-iron alloys, but, although the main factors are known with fair certainty, the problem is complicated by various subsidiary considerations and it cannot be said that a completely satisfactory explanation has yet been provided.

The earliest suggestions were that the great influence of heat treatment depended on the development or non-development of a precipitated phase or of a super-lattice structure. These ideas, however, have received no direct confirmation, while Jette and Foote‡ in an X-ray examination of 69 % nickel-iron could find no trace of a super-lattice even after annealing for more than 1 500 hours.

It has already been pointed out that the influence of interstitial impurities is much less than in pure iron, probably owing to increased solubility resulting from the face-centred cubic structure of the high-percentage nickel-irons. The internal strains due to impurities being thus reduced, magnetostrictive strains are likely to become more important, and it is therefore significant that magnetostriction of nickel-iron alloys changes sign at a composition (82 % nickel) near that at which the largest permeabilities are obtained (78·5 % nickel).

A relation between the disappearance of magnetostriction and the development of high permeability is confirmed by the results obtained on iron-nickel-copper alloys by Von Auwers and Neumann,§ who in addition to the initial permeability and coercivity also determined the magnetostriction of the various alloys. They found that the magnetostriction is zero for a series of compositions, entirely independent of heat treatment, which is represented in Figs. 7 and 8 by the line XY. This line is practically coincident with the zone of high initial permeability and low coercivity below 70 % nickel, and lies between the zones of high initial permeability for the two heat-treatments where these diverge near the nickel-iron line. These results show conclusively the close connection of magnetostriction with the development of the best properties in magnetically soft materials, although there appear to be complicating factors in the alloys containing more than 70 % nickel.

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* See Reference (67). † *Ibid.*, (70). ‡ *Ibid.*, (71). § *Ibid.*, (60).

It is of interest also in this connection that 1040 alloy, which has exceptionally high initial permeability, displays very small magnetostriction (5×10^{-7}), much less than that of 78·5 % nickel-iron.[*]

The predominance of magnetostriction in controlling the magnetic properties of these alloys also offers an explanation of the effect of cooling in a magnetic field. When, after cooling through the Curie point, the alloy is magnetized by an applied field, the appropriate re-orientation of the magnetic elements is produced and magnetostrictive stresses are set up in the ordinary way. If, however, the temperature is sufficiently high these stresses are relieved by plastic flow. Hence, if after cooling a field is applied in the same direction as before, the magnetic elements are already oriented and magnetostrictive stresses are greatly reduced. Magnetization is thus facilitated and a high permeability is obtained. If a field is applied in a perpendicular direction, on the other hand, the re-orientation necessary is increased and there is great mechanical resistance to magnetization so that the permeability in this direction is diminished.

The outstanding characteristics of nickel-iron alloys are thus attributable, in accordance with the general theory that elimination of internal strain is the principal factor in producing magnetic softness, to the reduction of magnetostriction. Complications are introduced, however, by crystal anisotropy and the variation of magnetostriction with the field strength. Thus the occurrence of the maximum effect of cooling in a magnetic field in the 65% nickel-iron, which Bozorth and Dillinger[†] suggested was connected with the Curie point of this alloy being the highest for the range in question, is attributed by Snoek[‡] to the fact that for this alloy the crystal anisotropy vanishes. The latter view is consistent with Dahl and Pawlek's observation[§] that iron and iron alloys, which have high Curie points, are little affected by applying a field during cooling, since these materials are strongly anisotropic. Moreover, in iron the magnetostriction is well known to vary irregularly with the field strength and even to change sign, so that a general avoidance of magnetostrictive strains is obviously difficult to achieve.

The differences between the compositions giving optimum magnetic properties and those for zero magnetostriction in nickel-iron and nickel-iron-copper alloys, and their dependence on heat treatment, have also not been finally explained. Randall[||] attributes them to local residual strains due to inequalities in cooling which, even with the utmost care, cannot be entirely eliminated. Lichtenberger[¶] and Snoek,[**] on the other hand, regard anisotropy as the main cause. Owing to the anisotropy of the magnetostrictive properties of crystals, the disappearance of the mean magnetostriction in a polycrystalline material does not imply a complete absence of magnetostrictive strains. It is suggested, therefore, that the composition at which maximum permeability is obtained is approximately the mean of the compositions for zero mean magnetostriction (82 % nickel), for the disappearance of magnetostrictive anisotropy (85·5 % nickel), and for the disappearance of magnetic anisotropy in the crystal (66 % nickel).

In view of the complexity of the factors involved and the possibilities provided by ternary and quaternary systems, as yet unexplored, further developments in alloys with favourable magnetic properties in weak fields are not unlikely.

Iron-Cobalt Alloys

In contrast to the properties of iron-nickel alloys, iron-cobalt alloys containing up to 70 % cobalt possess higher saturation flux densities than pure iron and generally compare favourably with other ferrous materials at flux densities above about 15 000 gauss. At magnetizing forces up to 50 oersteds the highest permeability is obtained in the 50 % alloy, the flux density at this magnetizing force being nearly 23 000 gauss, but at higher magnetizing forces the maximum shifts to lower percentages of cobalt, and the highest saturation flux density ($B - H$ = approximately 24 000 gauss) occurs in 35 % cobalt-iron. A serious limitation of these alloys is their low resistivity—less than 10 microhm-cm. in the region of highest permeability—and any attempt to increase this substantially is likely to reduce the flux densities at high magnetizing forces.

The 50 % cobalt iron is very brittle when cold, but by the addition of 1·7 % vanadium a great improvement in this respect is obtained,[*] so that cold rolling can be carried out successfully. Moreover, the resistivity is increased to over 20 microhm-cm. without serious deterioration in the magnetic properties. Owing to their high cost, however, the iron-cobalt alloys are comparatively little used, their principal applications being in apparatus for which weight-reduction is a primary consideration and in the pole-shoes of electromagnets producing intense fields, where the attainment of the highest possible flux density is desirable.

It is of interest that iron-cobalt alloys containing 78 %–95 % cobalt resemble the high-permeability nickel-irons in structure and in their small magnetostriction. Like the nickel-irons they also possess high permeabilities in weak fields, a maximum permeability of 30 000 in the 92% cobalt-iron having been recorded. Owing to their cost and to the superiority of nickel-irons in every respect except flux density in strong fields, they have not been developed commercially.

(4) MATERIALS WITH CONSTANT PERMEABILITY

For certain purposes, as in the continuous loading of telephone cables and in the cores of inductances for telephonic and radio circuits, where it is desired to avoid the wave-form distortion resulting from a large variation of permeability with magnetizing force, the maintenance of approximately constant permeability over a wide range of magnetization is more important than the attainment of high maximum or initial permeability.

The chief factors in obtaining constant permeability are (i) composition, (ii) heat treatment, (iii) introduction of air-gaps by fine subdivision, (iv) plastic deformation with or without dispersion-hardening. While more than one factor is generally involved in the production of any particular material, the constant-permeability characteristics are usually attributable primarily to one of these alternatives.

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[*] See Reference (62).
[†] *Ibid.*, (70)
[‡] *Ibid.*, (72).
[§] *Ibid.*, (67).
[||] *Ibid.*, (58).
[¶] *Ibid.*, (73).
[**] *Ibid.*, (72).

[*] See Reference (4).

Iron-Nickel-Cobalt Alloys

The chief example of the influence of composition in increasing the constancy of permeability under suitable conditions of heat treatment occurs in the range of iron-nickel-cobalt alloys developed by Elmen* and generally known as the "perminvars." In contrast to the effect of rapid cooling in increasing the permeability in nickel-irons, it was found that a "baking" treatment, consisting in heating for 24 hours at 400°–500° C. and then cooling slowly (after the usual annealing at about 1 000° C.), reduces the permeability but substantially increases its constancy in weak fields, especially in the alloys containing 65 %–75 % nickel. The addition of cobalt exaggerates this effect, which is found in greater or less degree in all the alloys containing between 15 % and 50 % of iron with the exception of a few extreme compositions in this region. Recently, similar properties have been demonstrated in alloys containing 50 %–90 % iron,† the initial permeabilities for these compositions being considerably smaller, however. The alloy containing 30 % iron, 45 % nickel, and 25 % cobalt displays very pronounced constant-permeability characteristics after baking, and it has been chiefly developed. In it a constant permeability of about 300 is obtained for field-strengths up to nearly 3 oersteds and hence for flux densities up to nearly 1 000 gauss. The resistivity of this alloy is low—approximately 18 microhm-cm.—but can be increased, as in the nickel-irons, by adding molybdenum or other suitable metals. A molybdenum content of 7 %, replacing iron, has been found suitable,‡ and increases the resistivity to 80 microhm-cm. While the initial permeability is increased to about 500, however, the range of field strength for which it is constant diminishes to less than 1 oersted.

For maximum flux densities within the range of constant permeability, the hysteresis loops are of negligible thickness and area, while at higher flux densities, loops of various irregular shapes, characterized by marked constriction near the coercive-force points, are usually—though not invariably—obtained. This type of loop is also obtained on a specimen built up from two constituents of very different magnetic properties in parallel, and its development in these alloys suggests that after baking a second phase is precipitated, possibly consisting in the formation of a super-lattice.

The perminvar characteristics are readily modified or destroyed, e.g. by high temperature§ or by tensile stress.‖ Cooling in a magnetic field, as already mentioned, produces great anisotropy, the maximum permeability being increased enormously parallel to the field but reduced in a perpendicular direction. The initial permeability in a perpendicular direction, on the other hand, is increased, so that the total range of variation is less than in the normal baked alloy, but the high degree of constancy in weak fields is destroyed.* In heavily cold-rolled material these effects are intensified, and perpendicular to the applied field an almost constant permeability of the order of 1 500 may be obtained at flux densities between 10 % and 60 % of saturation, but there is considerable variation in permeability at lower flux densities.† The remanence of this material also is very small, as in the isoperm type of material described below. Nishina‡ has recently shown that by cold-rolling the alloys having large iron-contents, the range of magnetizing force within which the permeability is constant may be extended up to as much as 7 oersteds. The permeability obtained, however, is reduced to about 60, so that the flux-density range is no greater than in the alloys containing smaller percentages of iron.

A limitation on the use of iron-nickel-cobalt alloys as constant-permeability materials is their liability to permanent alteration in magnetic properties through the temporary application of a large magnetizing force. Through such treatment the constancy of permeability may be reduced and the hysteresis loops restored to a normal, unconstricted shape. Ordinary demagnetization processes fail to remove the effect of the large magnetizing force, and the material can only be brought back to the constant-permeability condition by a fresh heat-treatment.

Powdered Materials

It is well known that the introduction of air-gaps into a magnetic circuit shears the effective B/H curve of the circuit, so that, while the apparent permeability is reduced, its constancy with varying field-strength is increased. This principle is most effectively applied in practice by pulverizing the material, and forms the basis of the powder cores or dust cores which have been widely used, particularly in telephone loading coils.

In the preparation of these cores the powdered magnetic material with a suitable insulating and binding medium is subjected to heavy pressure, so that a composite substance of specific gravity not much less than that of the original material is obtained. The permeability of the core depends less on the permeability of the original material than on the size of the particles, the thickness of the insulation between them, and the treatment which they undergo. The size of the particles also mainly determines the eddy-current loss but has little effect on the hysteresis loss for a given flux density, which depends chiefly on the hysteresis characteristics of the original material as modified by the mechanical and thermal treatment applied.

The permeabilities of the powder cores used in practice generally lie between 20 and 80, and the dimensions of the particles range from 0·005 to 0·1 mm. The principal materials that have been applied are electrolytic iron, silicon-iron, and, more recently, nickel-iron and carbonyl iron. The last has the advantage of being prepared in the form of particles of suitable size, thus obviating the pulverizing process.

The chief advantages of using very soft materials are the attainment of greater constancy at a given permeability and the reduction of the losses. As an example of the results obtainable in this type of material, powdered cores of 78·5 % nickel-iron can be prepared having a permeability of about 80 which is practically constant up to a magnetizing force of 1·5 oersted and does not vary more than 10 % up to 50 oersteds. The change in permeability produced by applying and removing a large magnetizing force is less than 0·5 %—a quantity which measures the stability, or rather instability, of the material and is an important characteristic of materials of this type.

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* See Reference (74).
† *Ibid.*, (63).
‡ *Ibid.*, (4).
§ *Ibid.*, (75).
‖ *Ibid.*, (76).

* See Reference (69).
† *Ibid.*, (67).
‡ *Ibid.*, (63).

In the last few years a number of powdered materials have been developed for the cores of inductances in radio-frequency circuits. Here the constancy of permeability with varying field-strength and the reduction of eddy currents are still more important. The materials are prepared on the same principles as before, but very fine subdivision is essential and particular care must be taken in the insulation of the particles. Typical products employ interleaved paper and bakelite as insulating media. Permeabilities range from 5 to 20, and are substantially constant up to large field-strengths.

Cold-worked Iron-Nickel Alloys

In order to avoid the complicated preparation of powdered materials, an attempt was made by Dahl, Pfaffenberger, and Sprung* to obtain the desired characteristics as properties of the material itself instead of as a consequence of the form in which it was prepared. An approach to the necessary combination of permeability, loss, and stability characteristics was found to result from severe cold-rolling of iron-nickel alloys containing 40 %–50 % nickel, but while each individual property could be obtained by an appropriate choice of composition, heat treatment, and degree of cold rolling, it did not at first appear possible to fulfil all the requirements simultaneously in the binary alloys. By the addition of 3 %–4 % aluminium or 10 %–15 % copper, however, alloys were produced which, after a final cold-rolling giving a reduction of 90 %, possessed magnetic properties which made them suitable for use as core materials, namely initial permeabilities of 30–80, varying only a few per cent with field strength up to 100 oersteds, with an instability not exceeding 1 %. Typical hysteresis loops for these materials (to which the name "isoperms" has been applied) are shown in Figs. 12(*a*) and 12(*b*); they display the characteristically low value of remanence with which high stability is associated, and the small area and consequent low hysteresis loss which is an essential property of a core material. The properties of these ternary alloys depend considerably on the heat treatment applied before the final cold-rolling, and a detailed study† of the effects of variations in composition, heat treatment, and cold working suggests that the influence of copper and aluminium (and, in a smaller degree, titanium) results from the presence of a precipitable constituent. It is believed that the cold working promotes precipitation and that the consequent internal stresses modify the magnetic behaviour of the material. As in dispersion-hardening of permanent-magnet materials, the maximum effect appears to be associated with an intermediate state attained before actual precipitation occurs.

More recently it has been shown,* however, that the third constituent is not essential to the development of the required characteristics. In the earlier investigation an initial cold-rolling giving a reduction of 50 % was employed and variations from 20 % to 80 % were found to have little effect on the properties of the final product. By increasing the degree of initial cold-rolling to reductions of 94 %–99 %, the desired permeability, loss, and stability characteristics can be obtained simultaneously in binary nickel-iron alloys. An essential condition is the development of strongly-marked crystal orientation, and, as would therefore be expected, the annealing temperature exerts a considerable influence, an increase from 800° to 1 000° C. reducing the hysteresis loss to less than one-third. The 40 % nickel-iron alloy, after initial cold-rolling to the reduction mentioned, annealing at 1 000° C., and finally cold rolling to a reduction of 60 %, gives a permeability of about 60, practically constant up to field strengths of 100 oersteds, with an instability less than 1 % and a hysteresis loss which, as shown by the loop in Fig. 12(*c*), is no greater than that of the iron-nickel-aluminium or iron-nickel-copper alloys.

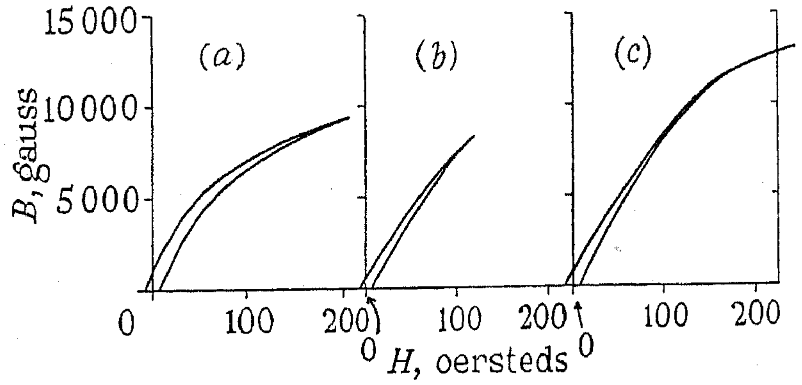

Fig. 12.—Hysteresis loops of cold-rolled nickel-iron alloys (Dahl, Pfaffenberger, and Sprung).

(*a*) Al-Ni-Fe, 90 % reduction.
(*b*) Cu-Ni-Fe, 90 % reduction.
(*c*) 40 % nickel-iron, severe initial cold-rolling.

An examination† of the directional variations of the mechanical and magnetic properties of the cold-rolled binary and ternary alloys, containing nickel and iron in the proportion 40/60, shows that the complete explanation of these properties depends not only on the development of crystal orientation and the precipitation of a dispersed phase, but on internal stresses and distortion of the lattice as a whole, produced by the cold rolling. As the effects of these factors may depend on the composition and original condition of the material as well as on its treatment, it is clear that extensive investigation is necessary if the behaviour of these cold-rolled alloys is to be fully understood.

CONCLUSION

The case of the materials having a high constancy of permeability, which have been described in the last section, provides a good illustration of the complexity of the factors controlling the properties of ferromagnetic materials. In view of the large number of operative variables, some perhaps still unrealized, and the comparatively small proportion of the whole field which has yet been explored, there seems no reason to doubt that further important developments, not only in the technical availability of the properties already attainable but also in the range of attainable properties, may be expected within the next few years.

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* See Reference (78).

† *Ibid.*, (79).

* See Reference (80).

† *Ibid.*, (81).

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* The abbreviations adopted here are those employed in *Science Abstracts*.

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DISCUSSION ON

"THE METERING OF MERCURY-ARC RECTIFIER SUPPLIES AND OUTPUTS"*

Mr. E. V. Clark (Australia) (*communicated*): It is somewhat surprising that, though the author points out clearly the fact that where waves are non-sinusoidal the power-factor value computed from accurate measurements of kilovolt-amperes and kilowatts generally differs from that computed from accurate measurements of kilowatts and kilovars, yet neither he nor any of the contributors to the discussion refer to two important facts in this connection. These are, firstly, that only in the simpler forms of circuit with non-sinusoidal waves can we say, without risk of misunderstanding, that the vars of reactive power are given by the expression

$$P_R = EI\sin\phi + \Sigma E_n I_n \sin\phi_n$$

and secondly, that even in the simplest form of balanced 3-phase loading, with non-sinusoidal waves of e.m.f. and current, our sine metering equipment, though quite independent of frequency when tested on sinusoidal waves, may fail to read correctly the vars as above defined.

To consider the first point: if we have a simple circuit of pure resistance and inductance, and apply an e.m.f. with an nth harmonic such as may be expressed by the equation

$$e = \sqrt{2}E\sin\omega t + \sqrt{2}E_n\sin(n\omega t + \theta)$$

then the current may be expressed by the equation

$$i = \sqrt{2}I\sin(\omega t - \phi) + \sqrt{2}I_n\sin(n\omega t + \theta - \phi_n)$$

where ϕ and ϕ_n are both positive angles not greater than 90°. In such a circuit, the power is given by the expression

$$P = EI\cos\phi + E_n I_n\cos\phi_n \text{ watts}$$

and the reactive power may logically be expressed as

$$P_R = EI\sin\phi + E_n I_n\sin\phi_n \text{ vars}$$

But now take a circuit consisting of resistance, inductance, and capacitance. With the same e.m.f. as before, the current may be that represented by the expression

$$i = \sqrt{2}I\sin(\omega t - \phi) + \sqrt{2}I_n\sin(n\omega t + \theta + \phi_n)$$

where ϕ and ϕ_n are again both positive angles not exceeding 90°, the difference between this case and the last being that now the fundamental of the current lags, whereas the harmonic current leads on the corresponding voltages. The power in this circuit is, as before,

$$P = EI\cos\phi + E_n I_n\cos\phi_n \text{ watts}$$

but it is doubtful whether we should express the reactive power as

$$P_R = EI\sin\phi + E_n I_n\sin\phi_n \text{ vars}$$

or as

$$P_R = EI\sin\phi - E_n I_n\sin\phi_n \text{ vars}$$

A sine meter independent of frequency which correctly reads the vars in the former circuit may be expected to give the smaller value of vars in this case, since such an instrument usually indicates whether the reactive power is lagging or leading. But common sense suggests that the higher value of the first expression should be taken; since if we accept the other as correct, one may readily construct, on paper, a circuit of inductance and capacitance which is 100 per cent reactive to both fundamental and harmonic, and yet the active power and the reactive power in the circuit are alike nil. The explanation of this anomaly is of course that whereas two powers of different frequency may neutralize one another, two reactive powers must be of the same frequency to do so, and hence to deduct harmonic vars from fundamental vars is about as useless as deducting the area of the ceiling of a room from the area of its walls.

In the case of the mercury-arc rectifier the conditions are still more complex, since the phase angle between current and volts may lie in any one of the four quadrants. The author's Table 2 shows three different quadrants for the phase angles of the fundamental and 2nd and 4th harmonics, for example. This gives no difficulty with regard to the active power, which remains

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* Paper by Dr. C. DANNATT (see vol. 81, page 256).

$$P = EI \cos \phi + \Sigma E_n I_n \cos \phi_n \text{ watts}$$

due regard being paid to the sign of each cosine. But it is quite useless to pay any regard to the sign of the sin ϕ's in the corresponding expression for the *total* vars of the circuit; and if any use can be made of such an expression the best form that it can take appears to be

$$P_R = EI \sin \phi + \Sigma E_n I_n \sqrt{\sin^2 \phi_n} \text{ vars}$$

with the stipulation that the roots to be taken must be all positive or all negative, in accordance with the sign of the first term.

Naturally, if we are dealing with a problem such as the determination of the reactive power on the high-voltage side of a 3-phase transformer supplying through independent secondaries two 6-phase rectifiers, one with 6-phase star connection and the other with 6-phase double zigzag connection, then the actual sign of each component of reactive power is important; but this, of course, is a horse of quite a different colour.

The second point is of minor importance in comparison with the first, in connection with mercury-arc rectifiers; though it is of theoretical interest, at least, in cases where we have a 3-phase balanced system with large harmonics, the circuit being such that the angle of lag of current upon volts is in the same quadrant for the fundamental and all harmonics. In such a circuit, the only rational expression for the reactive power is

$$P_R = EI \sin \phi + \Sigma E_n I_n \sin \phi_n \text{ vars}$$

where every term has the same sign, and the addition is therefore arithmetical.

Unfortunately, although our simple sine-meter methods of measuring the reactive power are independent of frequency when used on one frequency alone, they are not necessarily independent of frequency when connected for 3-phase measurement. One simple way of measuring the reactive power in a 3-phase balanced circuit of sinusoidal voltages and currents is to connect a single-phase wattmeter with its series coil in one phase and its voltage coil between the other two phase lines. A simple application of the vector diagram shows that the reading of this instrument multiplied by $\sqrt{3}$ gives the total reactive power of the system, $\sqrt{3}EI \sin \phi$; and the same result is readily derived trigonometrically. Further, by means of a reversing switch this wattmeter can be arranged to indicate whether the currents are leading or lagging. But if there are harmonics in the waves, when the vector method is no longer of use, it will readily be found trigonometrically that the direction of deflection due to a harmonic depends upon its order. Lagging reactive power of the harmonic order $(3m + 1)$ deflects the wattmeter in one direction, but that of harmonics of the order $(3m + 2)$ gives deflections in the opposite direction. The reading of such a wattmeter (in apparent watts) with balanced non-sinusoidal waves of voltage and current, all currents lagging on the corresponding voltages, is

$$P_R = EI \sin \phi + \Sigma E_h I_h \sin \phi_h - \Sigma E_k I_k \sin \phi_k$$

where h is a whole number of the form $(3m + 1)$, and k of the form $(3m + 2)$; harmonics of the order $(3m + 3)$ being, of course, non-existent.

Similarly, if we compute reactive power from the difference of the readings of two single-phase wattmeters with the usual connection, we again find that whilst this is correct for sinusoidal waves it is incorrect for non-sinusoidal waves, since here also the order of the harmonic determines which wattmeter should read the higher for reactive power due to lagging current. A sine meter of single-phase design should be immune from this kind of error; but wherever reactive 3-phase power is measured by a method which relies upon the balance of load and measures current in one phase against a voltage built up by use of another phase, it is unwise to assume, without investigation, that the result will be as we wish.

A little computation will show that if we have a non-sinusoidal single-phase circuit in which the power is given by

$$P = EI \cos \phi + \Sigma E_n I_n \cos \phi_n \text{ watts}$$

with due regard to sign; and if we determine in any way the reactive power given by the expression

$$P_R = EI \sin \phi + \Sigma E_n I_n \sin \phi_n \text{ vars}$$

then, whether we pay heed to the sign of the sines or not, if E_0 and I_0 are the r.m.s. values of voltage and current respectively, it is impossible that $E_0^2 I_0^2$ should be less than the sum of P^2 and P_R^2. As P_H^2 is of necessity a positive quantity, with minimum value zero, we may invariably set down the equation

$$E_0^2 I_0^2 = P^2 + P_R^2 + P_H^2$$

since there must be a value for P_H^2 to make this statement true. We are welcome to call P_H^2 the "square of the harmonic power," or the "missing link," or the "equalizing term," or anything else that we choose; but it is well to remember that P_H has no physical significance whatsoever. Further, the name "harmonic power," or "harmonic component of power" is a misnomer, since the magnitude of P_H depends on the relative magnitudes and phase angles of the harmonics rather than on their actual presence.

It can readily be shown that, in a circuit with non-sinusoidal waves, the necessary and sufficient conditions that $E_0^2 I_0^2 = P^2$ are:—

$$I/E = I_1/E_1 = \ldots = I_n/E_n = \text{a constant}$$

and

$$\phi = \phi_1 = \ldots = \phi_n = 0$$

and that in all other conditions, $E_0^2 I_0^2 > P^2$. And similarly, the necessary and sufficient conditions that $E_0^2 I_0^2$ shall equal $(P^2 + P_R^2)$ are that

$$I/E = I_1/E_1 = \ldots = I_n E_n = \text{a constant}$$

and

$$\phi = \phi_1 = \ldots = \phi_n = \text{a constant}$$

and that, in all other conditions, $E_0^2 I_0^2 > (P^2 + P_R^2)$.

In a circuit of pure resistance, we therefore find that $E_0 I_0 = P$, and that P_R and P_H are both zero; and it is simply because in simple circuits of lagging or leading reactance, with or without resistance, the above conditions do not hold, that in general if there is any reactive power in a circuit of non-sinusoidal waves we find that $E_0^2 I_0^2$ is greater than $(P^2 + P_R^2)$, and are tempted to postulate something called "harmonic power" to cover the deficiency.

In a circuit with sinusoidal waves, we can quite readily imagine an equivalent circuit with pure resistance and pure reactance concentrated in different parts; and we may then say, with some degree of logic, that the active component of the power wave of the whole circuit is identical with the wave of power in the pure resistance, and that the reactive component of the power wave is identical with the wave of power in the pure reactance. The reactive power component, of course, has zero average value; but it so happens that $EI \sin \phi$ is equal to its crest value, and hence forms a good way of describing it. The chief defect in the logic of this division is that, by arranging our equivalent circuit in series and in parallel form, we obtain different active-power and reactive-power components of the power wave, though naturally they have the same magnitudes.

But directly we have non-sinusoidal waves, we are likely to find it impossible to depict a circuit of pure resistance and pure reactance which shall take the identical current; and in the rare cases where we can, though

$$P = EI \cos \phi + \Sigma E_n I_n \cos \phi_n$$

is the average power in the pure resistance, there seems no logical reason for saying that the wave of power in the reactance may be appropriately indicated by the expression

$$P_R = EI \sin \phi + \Sigma E_n I_n \sin \phi_n$$

and, even if this wave is so expressed, we find that

$$E_0^2 I_0^2 > \left(P^2 + P_R^2\right)$$

Thus it seems that in using sine meters to measure reactive power supplied by mercury-arc rectifiers fed from 3-phase supplies, firstly, we are attempting to measure something which has no physical entity; secondly, we are hazy as to what we really wish to measure; thirdly, it is probable that our sine meters will measure something quite different from what we are after; and finally, even though we decide what we want to measure, and find some way of accurately measuring it, the result is quite useless from the point of view of determining the power factor of the circuit, as the author points out, except with the aid of a huge empirical factor.

Dr. C. Dannatt (*in reply*): Mr. Clark raises several points of theoretical interest in regard to the definition of the components of reactive kVA in non-sinusoidal circuits, and they are therefore relevant to the subject of metering in rectifier circuits.

In the paper it is assumed that the signs of the various harmonic reactive-kVA terms are significant and should be taken into account in the sum

$$P_R = \Sigma E_n I_n \sin \phi_n$$

From the point of view of assessing inherent meter errors in the tests reported in the paper, this was obviously the only attitude which could be adopted. From the more general standpoint, however, Mr. Clark is only expressing an opinion when he suggests that the absolute values of the separate terms should be considered, regardless of their signs. This is a matter which has been discussed by many writers, amongst whom there is no agreement as to whether the one or other convention should be adopted.

In a distorted circuit, neither the reactive kVA (P_R) nor the distortion power (P_D) have any physical significance, and indeed it is only in so far as separation of the two assists in the measurement problem that separation is worth while. The fact that P_R can only be measured when notice of the signs is taken seems a very strong argument in favour of doing so. An even stronger argument for adopting this course is that it avoids any ambiguity in the mathematical expressions for P_R and P_D. The distortion power on this basis is given by:—

$$P_D = \sqrt{\Sigma\left[E_m^2 I_n^2 + E_n^2 I_m^2 - 2E_m E_n I_m I_n \cos(\phi_m - \phi_n)\right]}$$

The fact that a reactive circuit may have P_R equal to zero, whilst P_D may be large, does not settle anything, although it is Mr. Clark's main reason for introducing the difficult convention

$$P_R = \Sigma E_n I_n \sqrt{\sin^2 \phi}$$

Mr. Clark's second point reduces to the statement that with certain meter connections for measuring P_R in a 3-phase circuit, reversal of phase rotation leads to a reversal of meter rotation. I agree with him that in 3-phase rectifier circuits in which it is wished to measure P_R a system of meter connections should be used which avoids this difficulty. For the tests reported in the paper the "two wattmeter" method was used, which is independent of phase rotation; but, in addition, the supply voltage was not distorted, so that in any case the difficulty was not present.

The problems raised by Mr. Clark serve to emphasize the view put forward in the reply* to the previous discussion, that in the effort to measure the "vars" of a rectifier supply-circuit the reactive-meter system is best avoided.

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* *Journal I.E.E.*, 1937, vol. 81, p. 275.

MACHINERY FOUNDATIONS*

By WILLIAM J. COZENS, B.Sc., Graduate.

(ABSTRACT *of Paper read before the* SCOTTISH STUDENTS' SECTION *at* EDINBURGH 27*th October, and at* GLASGOW 29*th October*, 1936.)

PURPOSE OF FOUNDATIONS

The following are the main functions of machinery foundations:—

(1) A foundation is required to maintain permanently the machinery fast in position, and level, with all parts in true alignment.

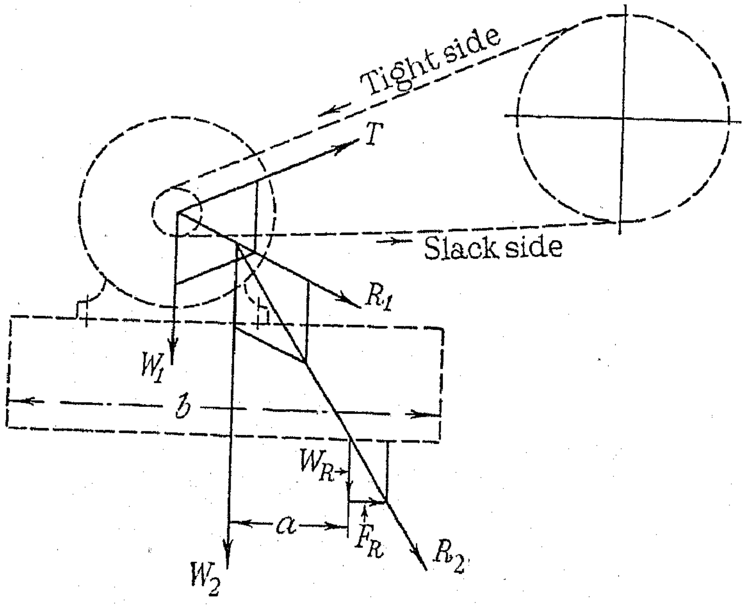
(2) A foundation is required to transmit the dead weight of the machinery to the ground or other supporting medium in such a manner that the safe bearing pressures are not exceeded.

(3) A foundation may be required to transmit the live load of the machinery to the ground or other supporting medium—i.e. to transmit the reaction of a belt, gearing, or other drive, or, in the case of a reciprocating machine, the thrust on the crankpin.

(4) A foundation is required to absorb, as far as possible, vibrations set up by the machinery so as to transmit as little as possible of this vibration to the surrounding ground or supporting medium.

TYPES OF MACHINERY

In regard to its effect on foundations, machinery may be divided into two main classes: (1) Machinery of a purely rotational type, e.g. turbine, electric motor, or generator. (2) Reciprocating machinery, e.g. steam, gas or oil engine, or ram pump.



Considering, first, Class (1), take the case of an electric motor driving line shafting by belt. As will be seen from the Figure, there are two sets of forces: (i) Dead weight of machine (= W_1) and dead weight of foundation (= W_2). (ii) Pull of belt (usually assumed as tension in tight side of belt acting through centre-line of shaft; in case of gearing, substitute thrust at pitch circle of motor pinion for pull of belt).

The following procedure is adopted in designing the foundation. Combine W_1 and T to obtain resultant (= R_1), using the parallelogram of forces. A preliminary guess is now made at the size, shape, and weight of foundation (= W_2), and its centre of gravity is obtained. W_2 and R_1 are then combined to give their resultant (= R_2). This resultant R_2 should cut the ground line within the "middle-third" of the foundation block, to give stability. That is to say, if a is the distance from the mid-point of the foundation to the point at which R_2 cuts the ground line, and b and c are respectively the length and the width of the foundation block, then a should not exceed $b/6$. Resolving R_2 into its horizontal and vertical components (= W_R and F_R respectively), the vertical forces are W_R and a couple of moment $W_R \times a$, while the horizontal force is F_R. The maximum vertical pressure is given by

$$(W_R \div bc) + (W_R a \div 1/6cb^2)$$

and should not exceed the values given in Table 3 or those obtained by experiment. The horizontal shear is equal to $F_R \div bc$, and should seldom exceed a few pounds per square foot. In no case should it amount to more than one-tenth of the vertical pressure.

Table 1

Type of engine	Ratio of weight of foundation to weight of engine
Steam engine (single-cylinder)	Not less than 4·0 : 1
Steam engine (compound) . .	3·75 : 1
Steam engine (triple-expansion)	2·5 : 1
Gas engine (single-cylinder) . .	3·0 : 1
Gas engine (2-cylinder) . .	3·0 : 1
Gas engine (4-cylinder) . .	2·75 : 1
Gas engine (6-cylinder) . .	2·25 : 1
Gas engine (8-cylinder) . .	2·0 : 1
Diesel engine (2-cylinder) . .	2·75 : 1
Diesel engine (4-cylinder) . .	2·4 : 1
Diesel engine (6-cylinder) . .	2·1 : 1
Diesel engine (8-cylinder) . .	1·9 : 1

The offset of the pulley (or gear-wheel) from the centre of the foundation block (= k) introduces a further couple whose moment is given by Q = (vertical component of T) × k which should be considered, especially if the drive is vertical. This couple is treated as before; thus:—

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* The original paper, of which this is an abstract, was awarded a Students' Premium by the Council.

Pressure to be added to maximum pressure as given above

$$= Q \div 1/6c^2b \text{ (not } Q \div 1/6cb^2\text{)}$$

As a rough approximation, the weight of the foundation may be taken as 3 to 5 times the weight of the electric motor (including base plate), if belt or gear drive is used; in the case of unit machines, e.g. rotary convertors, the ratio of weight of foundation to weight of machine is much lower, about 0·5 to 0·75.

Table 2

Type of Engine	Ratio of weight of foundation and weight of machinery (total)
Vertical steam engine (compound) coupled to generator	3·8 : 1
Vertical steam engine (triple-expansion) coupled to generator ..	3·5 : 1
Horizontal steam engine (cross-compound) coupled to generator ..	3·25 : 1
Horizontal steam turbine coupled to generator	3·0 : 1 to 4·0 : 1 (if of small output)
Vertical gas engine coupled to generator	3·5 : 1
Vertical Diesel engine coupled to generator	2·6 : 1

Turning to machinery in Class (2), foundations for reciprocating machinery are subject to fluctuating loads, out-of-balance forces, and vibration, and cannot easily be designed mathematically. It is necessary to provide a certain mass of foundation to absorb these forces and vibrations, and Tables 1 and 2 give average values for the ratio of weight of foundation to weight of machine. It should be noted that if the machine is badly balanced or liable to give rise to vibrations the weight of the foundation should be increased.

Table 3

Material	Maximum safe pressure (tons per sq. ft.)
Alluvial soil	less than $\frac{1}{4}$
Chalk (soft)	$\frac{3}{4}$
Chalk (hard)	3
Sand (dry)	1
Sand (fine and very compact)	3
Sand (firm and enclosed by sheet piling)	6
Clay (moist and soft)	$\frac{3}{4}$
Clay (yellow clay, dry)	2
Clay (London blue clay)	4
Clay (boulder clay, dry, in thick beds)	5
Clay (wet, in thin layers, inclined)	0
Gravel (ordinary)	3
Gravel (compact)	4
Rock (soft; sandstone, limestone, etc.)	2
Rock (medium; york stone, gritstone, blue limestone)	8
Rock (hard, in thick layers; granite, etc.)	in exceptional cases up to 75; usually not more than 30

With the aid of Tables 1 and 2 and a knowledge of the dead weight of the machine it should be possible to calculate the required weight of a foundation. In general, the shape in plan of the foundation block should resemble the bedplate, being from 4 ft. to 8 ft. longer in both directions; the depth may be calculated accordingly, but should be in proportion to other dimensions. In addition, a line drawn through the centre of the crankshaft of a horizontal engine and at an angle of 45° to the horizontal should cut the base of the foundation block, and not the end.

The average pressure on the ground is obtained by dividing the sum of the weights of the foundation and the machine by the base area of the block. Since this is an average value, and eccentric forces, irregular and angular thrusts, and similar forces, have not been considered, the pressure so obtained should not exceed two-thirds of the safe gearing pressure given in Table 3 for the appropriate soil. This Table gives average values of the maximum allowable working pressure on various types of ground. It is always advisable, if possible, to apply a test load to the ground and so determine a safe working pressure.

It should be noted that clay is most treacherous, especially if alternately wet and dry or if in thin layers. It is generally inadvisable to place a foundation block directly on hard rock, as vibrations are readily transmitted by rock; a cushion of 3 in. to 6 in. of cork or rubber may be placed below, and a 3-in. air space left round the block (if it is sunk into the ground) to " insulate " it from the ground.

DISCUSSION ON “A NOTE ON VOLTAGE INSTABILITY IN TESTING EQUIPMENT”[*]

Mr. E. V. Clark (Australia) (*communicated*): It is of much interest to me to learn that the conditions of instability which may be encountered when raising the alternating voltage upon a circuit consisting of an iron-cored choke and a condenser in series have been met with in actual testing, in a case where the capacitance present was merely the stray capacitance of leads and transformer winding to earth. I have hitherto regarded this particular experiment, which is usually carried out by my students, as of essentially an academic type, very useful in assisting to a better understanding of such things as the peculiarities of a coil of variable inductance, but as having little direct application outside the classrooms. That the shifting of the earth point from one terminal of the choke to the other should make such a great difference to the test results must have been exceedingly perplexing to those carrying out the test described, the explanation being far from self-evident, even when pointed out.

There is a slight inaccuracy in the author's description of the elucidating experiment and its theory, in that he says, with reference to his Fig. 3: “If, therefore, the resistance is very small, g will almost coincide with h.” This is not the case, as the line gh represents a voltage compounded of the power component of the fundamental and the harmonics introduced by the variable inductance of the choke. As it is upon this variable inductance that the experiment hinges, it is inevitable that the harmonics in the waves should be considerable. An oscillographic view of the voltage and current waves as the experiment is carried out should prove illuminating, though the change from current lagging to current leading would probably be somewhat masked by the size of the harmonics.

In carrying out in the laboratory an experiment to obtain curves such as those of Fig. 3, I arrange a condenser, iron-cored choke without air-gap, and rheostat of suitable range, in series with one of the laboratory alternators equipped with potentiometer-type field control. Keeping constant excitation on the alternator, one can trace the whole curve $Og'dgd_1E_s$ of the figure in both directions, by varying the series rheostat, the ohmic drop of which eliminates the instability of the circuit. Then, on short-circuiting the rheostat, one can trace the upward and downward unstable curves, $Og'dd_1E_s$, and $E_sd_1gg'O$, by varying the alternator excitation. However, on such a test, the lines dd_1 and gg' are found to be not quite horizontal, d_1 and g being somewhat higher than d and g' respectively, since the change from lagging to leading current (or vice versa) appreciably affects the voltage of the small alternator used for the test. If a multiple switch is provided for the voltmeter, in order that the voltage across the condenser, the choke, and the two together, may be read, one obtains also the curves ObE_L and OcE_C of Fig. 3, so that the experiment carries its explanation with it.

Prof. H. B. Dwight (U.S.A.) (*communicated*): The paper describes an interesting phenomenon which is sometimes of considerable importance. While the change in current may be traced out, as described in the paper, by varying the voltage applied to the circuit containing an iron-cored reactor and a condenser, the phenomenon is usually encountered in a disconcerting manner, as first a high voltage and then a low voltage is obtained across the reactor upon repeatedly closing a switch. This occurs in an erratic manner. Both the small and the large voltages are quite stable for a given applied voltage, and which of these is obtained depends on the part of the cycle at which the switch is closed.

This has at times been a real danger to apparatus. For instance, when observed by connecting a transformer between generator terminals and earth, it resulted in an unexpectedly high voltage which punctured the generator insulation in several instances.[†] At another time, when connections were made for the purpose of applying about 110 kV to test an insulator, the use of an iron-cored choke coil resulted in more than twice that voltage being applied.[‡] In the paper just referred to, other instances are also described.

It has not been definitely shown under what conditions an iron-cored reactor or earthing transformer is safe from giving an abnormal and dangerous voltage. It is known that iron-cored reactors are used as Petersen coils, connected in series with the capacitance of a transmission line, and apparently no trouble results. Possibly a large air-gap in the core of the reactor is sufficient safeguard.

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[*] Paper by Prof. B. L. Goodlet (see vol. 80, page 490).

[†] H. B. Dwight and C. W. Baker: “Double Voltages in Circuits having Capacity and Inductance,” *Electric Journal*, 1911, vol. 8, p. 1102.

[‡] H. B. Dwight: “Abnormal Behaviour of Iron-cored Reactors in Condensive Circuits,” *ibid.*, 1924, vol. 21, p. 324, Fig. 4.

INSTITUTION NOTES

COOPERS HILL WAR MEMORIAL PRIZE AND MEDAL

The triennial award of the above Prize and Medal, which fell in 1937 to The Institution, has been made by the Council to Dr. T. E. Allibone, Associate Member, for his paper on "The Mechanism of the Long Spark."

THE INSTITUTE OF FUEL

Members of the I.E.E. are cordially invited by The Institute of Fuel to attend a meeting of that Institute to be held on Thursday, 31st March, at 6 p.m., when a paper by Dr. S. Livingstone Smith and Prof. C. H. Lander, entitled "A Comparison of the Cost of Heat Supply by Electrode Boiler or by Coke Boiler to the Same Group of Buildings," will be read and discussed. The meeting will be held at The Institution of Mechanical Engineers, Storey's Gate, S.W.1.

A limited supply of advance copies of the paper will be available about 10 days before the meeting, and any member of the I.E.E. desiring to receive a copy should apply to the Secretary, The Institution of Electrical Engineers, Savoy Place, London, W.C.2.

SCHOLARSHIPS

The Secretary desires to draw the attention of members to the following Institution Scholarships:—

Duddell Scholarship (value £150 per annum for 3 years).

Open to British subjects under 19 years of age on the 1st July who have passed a matriculation or equivalent examination, and who desire to take up a whole-time day course in electrical engineering.

Ferranti Scholarship (value £250 per annum for 2 years).

For whole-time research or post-graduate work. Open to British subjects under 26 years of age on the 1st July, who have been Students or Graduates of The Institution for at least 2 years and have taken either (*a*) a whole-time course in electrical engineering of at least 3 years and obtained a degree or diploma; or (*b*) a whole-time course in science of at least 3 years and obtained an honours degree, provided that in the final examination for such degree they have passed in "physics," or "electro-chemistry," or "electro-metallurgy."

Swan Memorial Scholarship (value £120 for 1 year).

The conditions are similar to those for the Ferranti Scholarship, except that the age limit is 27 years on the 1st July and that candidates need not be members of The Institution. Preference will be given to candidates who were born in the County Borough of Sunderland, or resided there for at least 7 years, or were educated at Sunderland Technical College.

Silvanus Thompson Scholarship (value £100 per annum, plus tuition fees, for 2 years).

Open to British subjects who have served a minimum apprenticeship (or its equivalent) of 3 years at an approved works and are under 22 years of age on the 1st July, and who desire to take up a whole-time day course in electrical engineering.

The closing date for receiving nominations for this year's awards of Scholarships is the 15th April. Any member desirous of obtaining more detailed information should apply to the Secretary.

ELECTIONS AND TRANSFERS

At the Ordinary Meeting of The Institution held on the 24th February, 1938, the following elections and transfers were effected:—

Elections

Associate Members

Binny, John Graham.
Dolan, Harry.
Erskine, Ronald Albert, B.A.
Franks, Henry Bertram S.
Gentry, Frederick Charles, B.Sc.
Gibson, Stanley Watts.
Horn, Cyril Onslow, B.Sc.
Kay, Dudley.
Lanphier, Robert Carr, B.Sc.
Legg, James.
Legood, Frederick John.
McGavin, James, M.Eng.
McLaren, Colin Colby, B.A.
Mitchell, John Archibald G.
Moffat, Bryce Fulford, B.A.
Sharpe, Harry Derwent, B.Eng.
Sims, Alfred Henry.
Trussler, Howard.
Wadsworth, George Wade, B.Sc.Tech.
White, Cyril Spencer, B.Sc.

Companions

Gray, Charles Henry, B.A.
Hacker, Gustave.
Milford Haven, The Most Hon. The Marquess of, G.C.V.O.

Associates

Auchterlonie, George Robert.
Barnacle, Alfred Benedict.
Billett, William Fred.
Binns, Clifford.
Booth, Leslie Arthur.
Brown, William Reginald F.
Clark, David James.
Cloke, Herbert William B.
Craig, Robert.
Gaunt, Gerald Lewis.
Kelman, Edgar Raymond.
Remfry, Arnold Edwin.
Smith, William Henry.
Taylor, George.
Waldeck, Thomas Ernest.
Wilson, Arthur Henry.

Graduates

Andrews, Andrew Mathews.
Aspin, John James E.
Bailey, Albert Thomas.
Bailey, Henry Patrick, B.Sc.(Eng.).
Bhawalkar, Devidas Raghunathrao, Ph.D.
Bird, William Arthur.
Bridgwood, Thomas Graham, B.Sc.
Brocklesby, Frederick Norton.
Brown, Eric Frank.
Burton, Geoffrey Greenwood, B.Sc.
Campbell, James.
Coles, Richard Geoffrey H., B.Sc.
Crowe, Edward.
Farmer, William Herbert.

Graduates—continued.

Forte, Lancelot Francis, B.Sc.(Eng.).
Franklin, Alfred Leslie.
Furse, Charles William, B.A.
Garnett, Wilfred Harold.
Garson, Archibald Alan, B.A.
Goodwin, John Charles, B.Sc.Tech.
Griffith, Rhodri Pennant, B.Sc.
Griffiths, Alfred.
Hall, Robert Henry.
Hammersley, Harold Ewart B.
Hands, Douglas Cyril.
Hatfield, Stanley Arthur.
Henn-Collins, Christopher Arthur.
Holdsworth, Leonard.
Holmes-Smith, Edgar, B.A.
Hurn, Mark, B.Sc.(Eng.).
Husbands, Eric William C., B.Sc.
Jacobs, Paul Geoffrey.
Jordan, Frederick William.
Joslin, Cyril George E.
Litchfield, Wilfred.
Lloyd-Jones, Arthur Edward.
Lowery, George, B.Sc. (Eng.).
Lowne, Hugh Reginald B.
McCarthy, Terence, B.E.
Majeran, Henryk Harry.
Malegamvala, Dinshaw Kaikhushroo.
Mason, Henry James S., B.Sc.(Eng.).
Moffatt, Thomas Stanley, B.E.
Mohsin, Mohamed Shawki, B.Sc.
Murray, Hugh Younger, B.Sc.(Eng.).
Neville, Arthur.
Noble, John Oswald.
O'Sullivan, Rex Adalbert.
Padmanabhan, G., B.A.
Payne, Cyril Frederick E., B.Sc.
Parr, Asa.
Perkins, Henry Whitworth.
Ridley-Martin, Michael Grey.
Roberts, Walter George, B.Sc.(Eng.).
Rothwell, Herbert Lees.
Seddon, Fred.
Smith, Kennett Oldham.
Stockton, Donald Arthur.
Straughen, Alan Robert, B.Sc.
Turner, William Aylmer L. B.A.
Vadi, Malli Mantra, B.Sc.
Varshneya, Satish Chandra.
Watts, Basil Kingsford.
Wright, Eric, B.Sc.
Wright, Shirley Edwin M., B.Eng.
Wylie, Thomas Stanley.

Students

Alexander, William David.
Atkinson, Leonard.
Baines, Denis.
Ball, Grayham John S.
Bana, Sorabji Dorabji, B.Sc.
Betterton, Ernest Charles.
Bickley, Leonard James.
Bowker, Frank.
Buchan, James Welch R.
Burn, John Faulder.
Buss, Donald Arthur.
Cater, Douglas Julian.
Clark, Thomas Foster.
Clough, Frederick Davenport.
Cook, Ronald Leslie J.
Cox, Eric Henry.
Davies, Cecil Harold.
Drake, Philip John.
Felgate, Peter Edward.
Garrett, Richard Gerald W.
Gatley, John Barker.
George, Pullikapparambil Varugis.
Goddard, George Horace.
Goodall, William James.
Green, Kenneth Cecil.
Griffiths, Robert Kendall.
Guttery, Denis Roland C.
Hampson, Henry Gordon.
Hancock, William Thomas M.
Harker, Sydney Robert.
Harvey, John Alistair F.
Houghton, Thomas.
James, Alfred Radcliffe.
Jamieson, Ian Alastair.
Jarratt, Herbert.
Jay, James Bertram.
Knott, Cecil Saunders.
Knowles, Kenneth William.
Lall, Brij Mohan.
Legood, Arnold Samuel.
Lister, Harold.

Students—continued

McNulty, Thomas Edward.
Mansingh, Jit Ranjit.
Masters, Sydney Herbert.
Minus, Herbert Cecil.
Muret, Douglas Adrian.
Mylam, Alfred Sydney.
Nair, Chembakamangalathu Krishnan.
Nelder, Norman John.
Payne, John James.
Penver, Arthur William.
Platt, Henry.
Pope, Alfred Edgar.
Prest, Bernard Hudson.
Radford, Arthur Hedley.
Rivers, Basil Winson R.
Rogers, Anthony Gusterson.
Salisbury, Raymond Albert.
Sandercock, Kenneth Norman.
Sanderson, Joseph Mackenzie.
Shaw, Donald.
Shepherd, David Ian.
Shrubb, Kenneth Frederick.
Sinha, Anil Kumar.
Smith, Edward Cyprien.
Southern, Christopher John.
Taylor, Wilfred.
Thomas, John Charles.
Vigors, Philip Doyne.
Wadely, Michael.
Walker, Edward Humphries.
Wallis, James Grainger.
Wilkinson, Norman Edward R.
Wills, William John A.
Winnard, James.
Wooller, Maurice Philip.

Transfers

Associate Member to Member

Aisenstein, Simon M.
Dixon, William.
Donnelly, Wilfrid, B.Sc. Tech.
Edwards, Edward.
Ellis, Herbert Willoughby.
Guilford, Alfred Leslie, B.Sc.Tech.
Jordan, Francis Victor.
Loftus, James John.
Lunn, Edgar.
Metz, Gerald Louis E.
Meyers, Arthur Lennox, B.Sc.(Eng.).
Muirhead, Andrew Bruce.
Pearson, Stephen Oswald, B.Sc.(Eng.).
Pimble, Cyril Charles.
Rolfe, George Berkeley, B.Sc.(Eng.).
Spencer, Thomas George.
Thomas, Horace Augustus, D.Sc.

Associate to Associate Member

Howles, Leonard.
Ledward, Thomas Archibald.
Tilstone, George.

Graduate to Associate Member

Barton, Richard Bernard, B.Sc.
Beard, John Cecil, B.Sc. (Eng.).
Binns, Joshua William.
Boud, Frederick Harry.
Britton, Geoffrey Alan C. R.
Chapman, Ernest Edward.
Chatterjee, Hari Prasad, B.Sc.
Coles, Raymond Scofield, B.Sc.
Comrie-Smith, George Stuart.
Cowell, Antony Russell, B.A.
Crofton, Robert Denis.
Dean, Shaikh Mehr, B.Sc.
Gould, Gerald Hopwood.
Graham, Bertram.
Grieveson, John Alan, B.A.
Grubb, Edward Joseph, B.Sc.
Harris, Frederick Henry.
Hegan, Alec.
Higgs, Victor Alexander, B.Sc.
Howlett, Francis Charles.
Ingman, Hemming Eric, B.Sc.(Eng.).
Irons, John McAdoo.
Jefferson, Sidney, B.Sc. (Eng.).
Jones, Norman William.
Lillie, Herbert.
Lowe, Bernard.
Mackley, Jack, B.Sc.(Eng.).
Mahal, Bakhshish Singh.

Graduate to Associate Member—continued.

Minter, Geoffrey.
Ogilvie, George Parry.
Parker, Harry.
Sengupta, Monoranjan, B.Sc.
Smith, Frederick George, B.Sc.(Eng.).
Speedy, Gordon Maxwell E.
Theobald, Stanley.
Watson, Ronald, B.Sc.
Westell, Edgar Philip L.
Wise, Norman.
Zaki, Said.

The following transfers were effected by the Council at their meeting held on the 3rd February, 1938:—

Student to Graduate

Angold, Edward Barnabas, B.Sc.
Barker, Clifford.
Bayliss, William Channing, B.E.E.
Beck, Arnold Hugh W., B.Sc.(Eng.).
Bell, Robert Herbert.
Bentley, Hugh Roland B.
Booth, Gilbert.
Brown, Geoffrey William.
Bullen, Harold Howe.
Burke, Clifford Leonard L.
Candy, Bernard Osborne, B.Sc.(Eng.).
Carrasco, Hilary Baptist.
Carrothers, John Kelly.
Chatterton, Rex John B.
Clapham, John Anyan.
Clarke, Douglas.
Clemett, John, B.Sc.
Cobban, James.
Cooper, Stanley, M.Eng.
Cross, Cyril Austin.
Dasgupta, Amal Kumar.
Dobson, Arnold Tidswell.
Dykes, James Oswald, B.Sc.
Easton, Kenneth John.
Eckett, Sidney Wallace.
Edmonds-Brown, Harold Edward.
Elder, John Alexander, B.Sc.
England, Ralph.
Evans, Alwyn.
Facey, John Morris C., B.Sc.(Eng.).
Fawssett, Phyllis Armorel M. (Miss).
Ferguson, John McIntyre, B.Sc.
Finnis, Ronald Tavenor.
Florida, Charles David.
Flux, Robert William.
Gates, Norman Percival.
Gall, Melville Ernest.
Hales, Arthur Collingwood, B.Sc.(Eng.).
Hayward, Rodney Kenneth, B.Sc.(Eng.).
Hetherington, Clifford.
Higgins, William Godfrey G.
Hilyer, Frederick Gordon.
Hussain, Syed Naseer.
Jeffery, Derek William.
Jenkins, Llewelyn Evans.
Kanhere, Sharngdhar Purushottam, B.Sc.Tech.
Kirpalani, Mangho Jeramdas, B.Sc.Tech.
Krishnan, Rishiyur Subrahmanyam.

Student to Graduate—continued.

Lawrence, Harold Herbert.
Lawson, William.
MacGregor, James Gillespie.
Mackay, Neil John.
Mackenzie, Roderick, B.Sc.
McNeil, John David, B.Sc.(Eng.).
Mahmoud, Hamman, B.Sc.
Marshall, John Carlile.
Masonparry, Kenneth.
Masters, Edward Frederick O., B.Sc.(Eng.).
Mendis, Terence William.
Mercer, John Francis W., B.Sc.(Eng.).
Mills, Christopher Stanley, B.Sc.(Eng.).
Montgomery, Denys, B.Sc.(Eng.).
Morrison, John.
Myers, Thomas McGowan.
Normington, Alfred Charles, B.Sc.(Eng.).
Parry, Reginald Charles.
Pugh, David Bligh.
Ruddock, Gerald Arthur, B.Sc.(Eng.).
Rushton, John Harold.
Scarrott, Gordon George.
Scutt, Winston Marvin.
Smillie, Ronald.
Soar, Gerald Burgess.
Squires, Mordecai.
Steng, Malcolm John N.
Stokes, Morris Amos.
Terrell, Basil Joseph.
Tessier, Roger Leslie C.
Treasure, Vivian Roy S.
Tucker, Maurice Albert.
Walker, Donald Clark.
Walker, Ernest Harold.
Walker, Philip Hulme, B.Sc.(Eng.).
Ward, Arthur Leslie.
Williams, Arthur Parry.
Wilson, Joseph Shevlin, B.Eng.
Wimpenny, Norman.
Woodward, Harry.

The following transfers were also effected by the Council on the 24th February, 1938:—

Student to Graduate

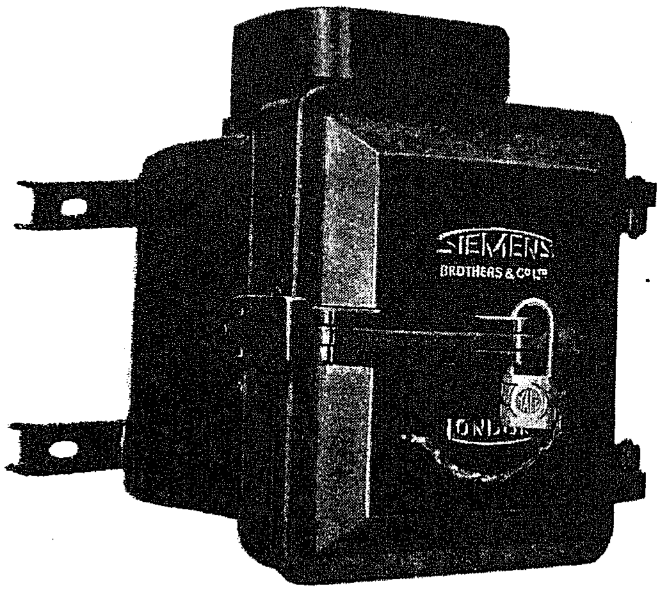
Biden, Guy William V.
Bland, Sydney, B.Sc.
Bowker, George Dickinson.
Briggs, George Eric.
Chester, Albert Eric, B.Sc.
Claxton, Sydney George.
Crawshaw, Geoffrey.
Davis, Timothy.
Dracup, Arthur.
Everitt, Horace George.
Francis, William David.
Hill, Ernest.
Joseph, Edward.
Kydd, James Mackay B.
Marks, David John, B.Sc.(Eng.).
Meaden, Jasper Frederick.
Richardson, William Eric.
Salmon, Frederick Henry.
Sankey, Richard Graham.
Smith, George Christopher.
Smith, Henry Rae.
Spencer, Gordon Arthur.
Telfer, Henry.
Whitton, George Alexander.
Williams, Thomas Norman.

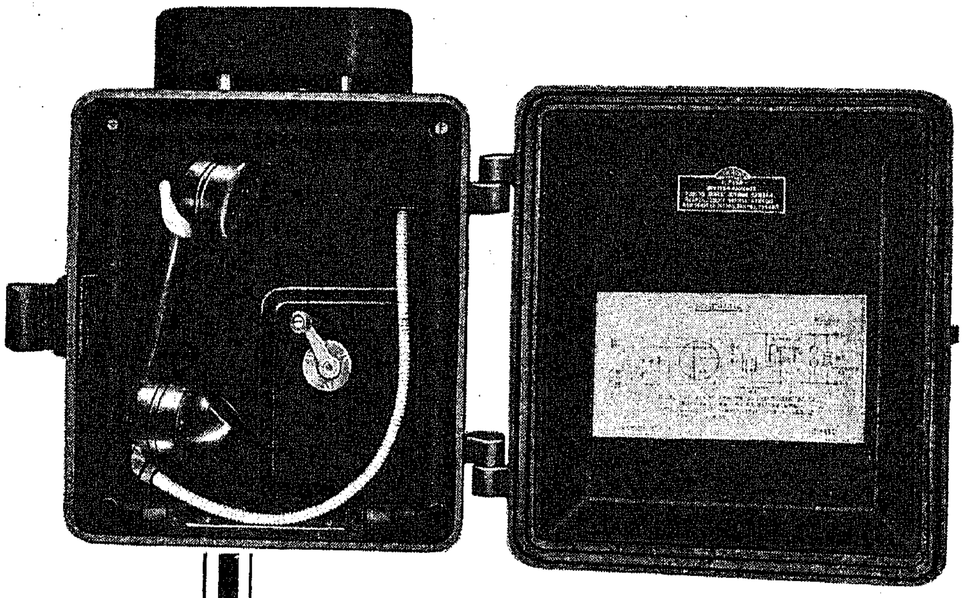
SIEMENS

"NEOPHONE"

WEATHERPROOF
MAGNETO TELEPHONE

for
Traction Routes, Police Services,
Ambulance Call Systems,
etc.

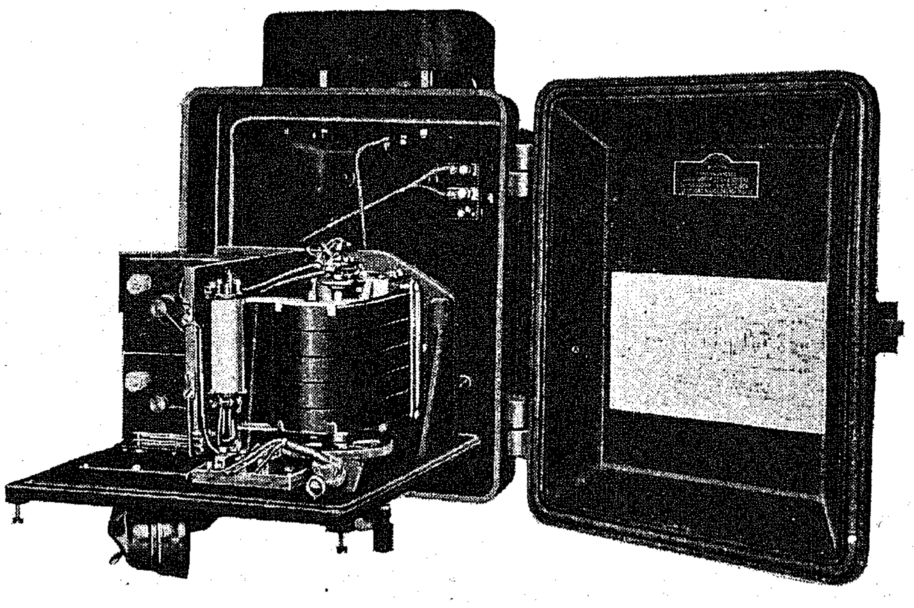




SIEMENS "NEOPHONE" THE WORLD'S MOST EFFICIENT TELEPHONE

A special feature is the employment of a "Neophone" handset in place of the fixed transmitter and separate receiver generally fitted on telephones of this kind. This not only makes it very convenient to use, but also provides the unrivalled transmission efficiency and superior articulation for which the "Neophone" is noted.

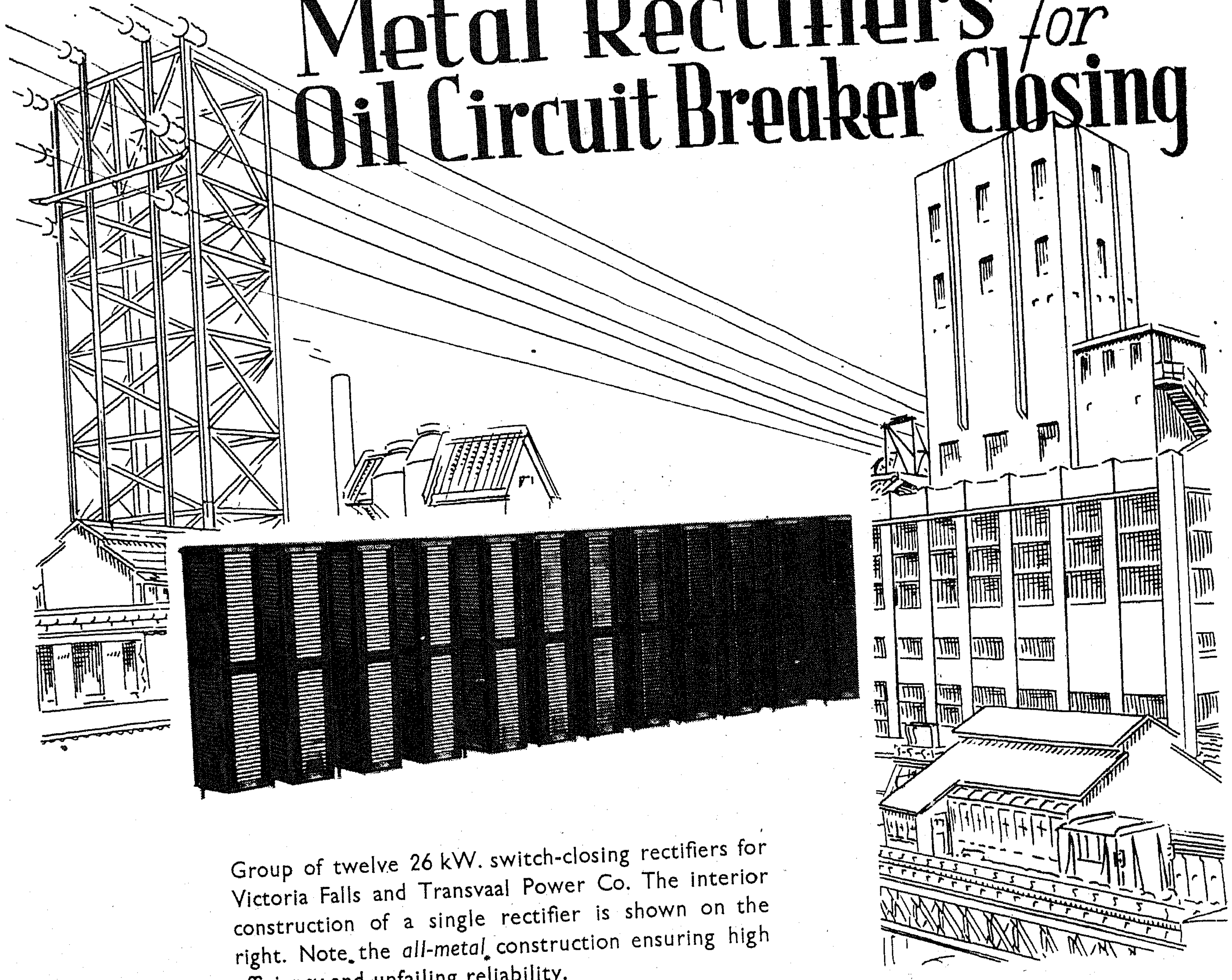
In addition, the incorporation of our patent anti-sidetone circuit enables conversations to be carrried on comfortably in noisy situations.



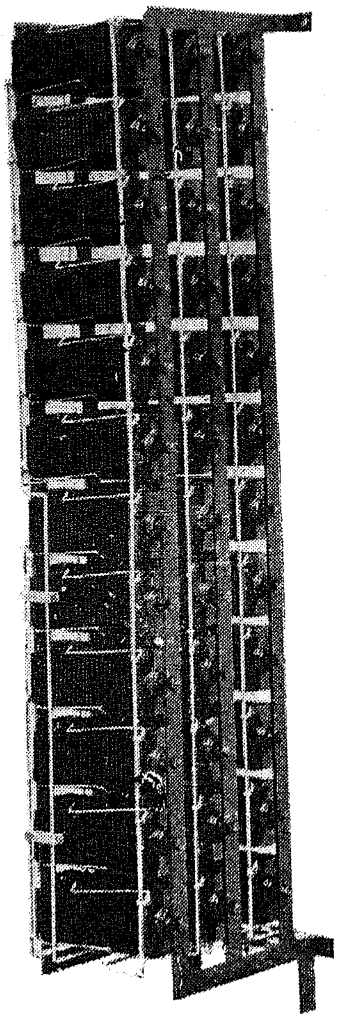
SIEMENS BROTHERS & CO., LIMITED
WOOLWICH, LONDON, S.E.18.

Telephone : Woolwich 2020.

Metal Rectifiers for Oil Circuit Breaker Closing



Group of twelve 26 kW. switch-closing rectifiers for Victoria Falls and Transvaal Power Co. The interior construction of a single rectifier is shown on the right. Note the *all-metal* construction ensuring high efficiency and unfailing reliability.



Westinghouse Metal Rectifiers provide the most reliable and efficient means of closing oil circuit breakers. They need none of the attention and maintenance associated with alternative methods and will give just as efficient service as the actual switchgear. Once installed, their reliability makes their presence forgotten. As only one solenoid is operated at a time, one rectifier may be used to control a number of switches. Write for booklet D.P.11 I.E.E. for full details.

WESTINGHOUSE

METAL RECTIFIERS

THE WESTINGHOUSE BRAKE & SIGNAL CO. LTD.

82, YORK WAY . KING'S CROSS . LONDON, N.1

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- The Anchor Cable Co. Ltd.
- British Insulated Cables Ltd.
- Callender's Cable & Construction Co. Ltd.
- The Craigpark Electric Cable Co. Ltd.
- Crompton Parkinson Ltd. (Derby Cables Ltd.)
- The Enfield Cable Works Ltd.
- Edison Swan Cables Ltd.
- W. T. Glover & Co. Ltd.
- Greengate & Irwell Rubber Co. Ltd.
- W. T. Henley's Telegraph Works Co. Ltd.
- The India Rubber, Gutta-Percha & Telegraph Works Co. Ltd. (The Silvertown Co.)
- Johnson & Phillips Ltd.
- Liverpool Electric Cable Co. Ltd.
- The London Electric Wire Co. and Smiths Ltd.
- The Macintosh Cable Co. Ltd.
- Pirelli-General Cable Works Ltd. (General Electric Co. Ltd.)
- St. Helens Cable & Rubber Co. Ltd.
- Siemens Brothers & Co. Ltd. (Siemens Electric Lamps & Supplies Ltd.)
- Standard Telephones & Cables Ltd.
- Union Cable Co. Ltd.

" To equip my Machines with C.M.A. Cables costs me only 6½d. per Machine more than cables from other sources. After what I have seen in your Works of the care taken in their manufacture I am advising my Directors to sign up with your good-selves for our Cable requirements."

The Policy of the C.M.A. is QUALITY

C.M.A.

C.M.A. Regd. Trade Mark Nos. 422219-20-21
NONAZO Regd. Trade Mark No. 458865

CABLES

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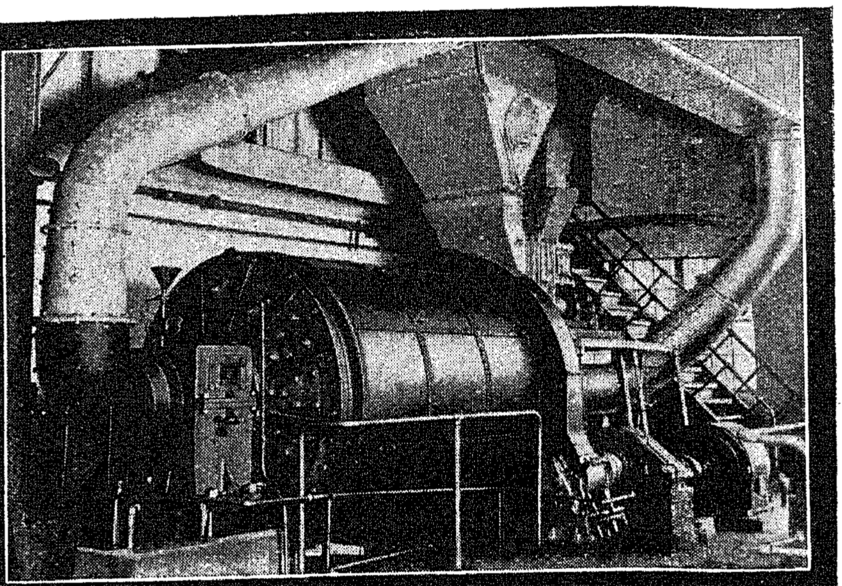
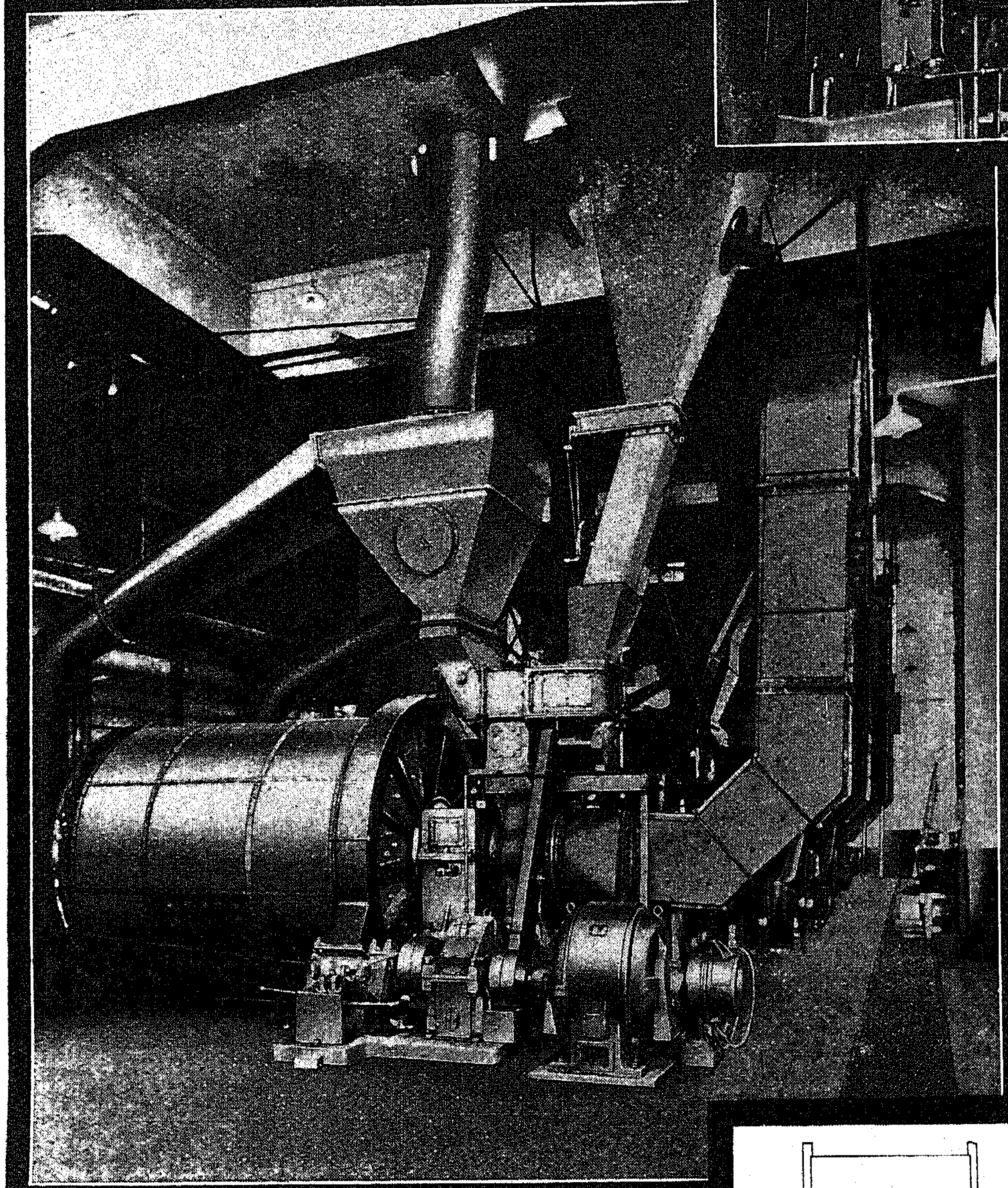
Advt. of the Cable Makers' Association, High Holborn House,
52-54, High Holborn, W.C.1. *Phone: Holborn 7633*

BABCOCK PULVERISED FUEL EQUIPMENT



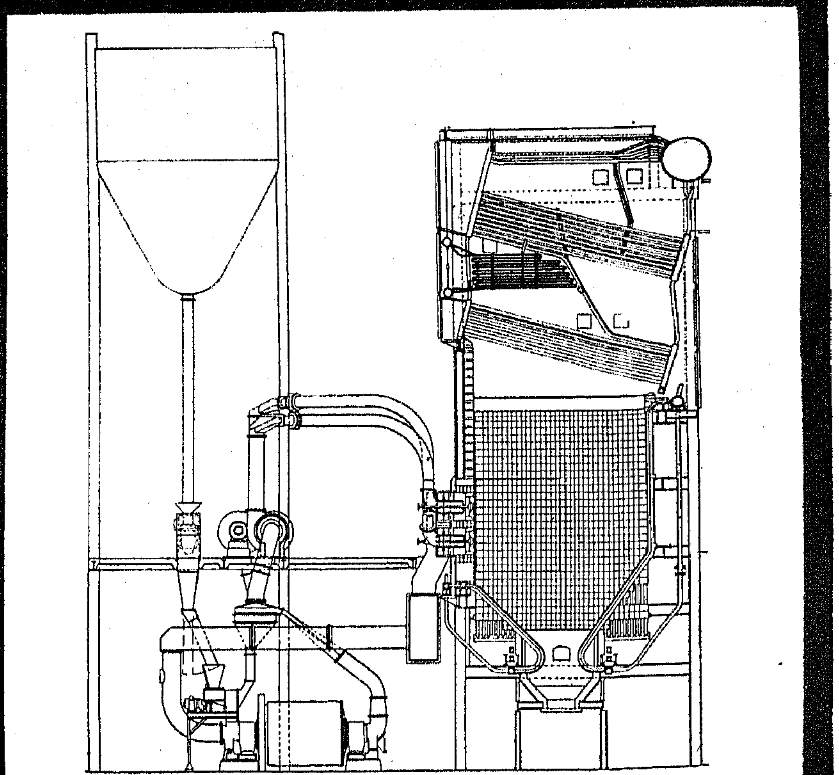


THE BABCOCK & WILCOX TUBE MILL

THE Babcock & Wilcox Tube Mill—which is a development of the well-known Fuller Bonnot Mill—is manufactured in a range of sizes for capacities from 5 to 15 tons of pulverised fuel per hour. It has already gained a world-wide reputation for reliability and low maintenance costs. The illustrations show two typical installations and the diagram below shows the simple layout of the direct fired system.

THE Babcock & Wilcox Tube Mill, though designed to meet the requirements of the direct fired system, can also be used in conjunction with the storage system, being specially suited for the pulverisation of anthracites and fuels of low grindability.

Where space occupied is not of prime importance this mill has much to recommend it, particularly for consistent fineness of grinding—so important for the firing of metallurgical furnaces, in which application it is giving highly satisfactory results.

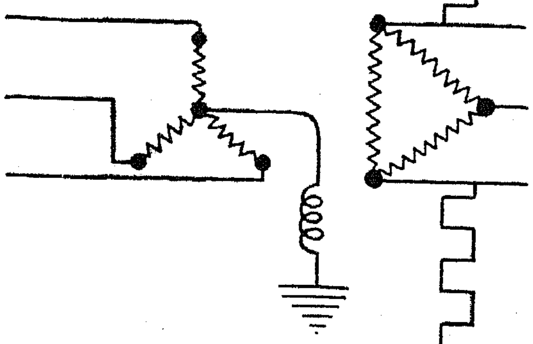


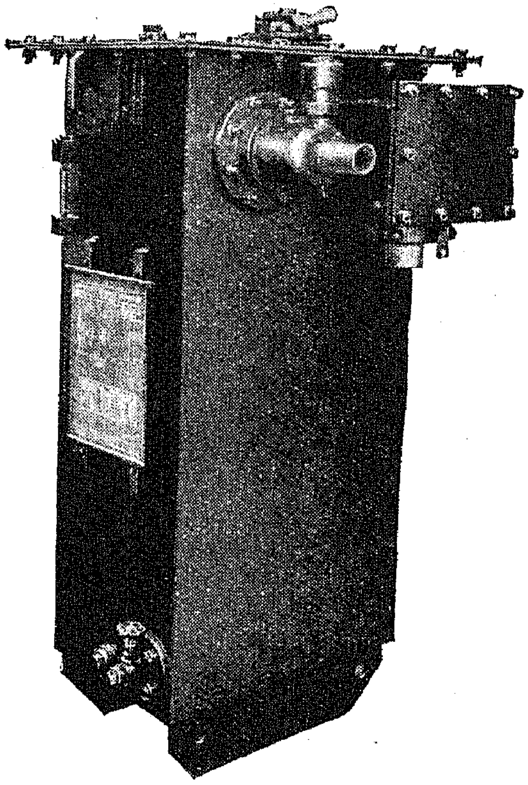
BABCOCK & WILCOX Ltd., 34 FARRINGDON STREET, LONDON, E.C.4

Ensure CONTINUITY OF SUPPLY

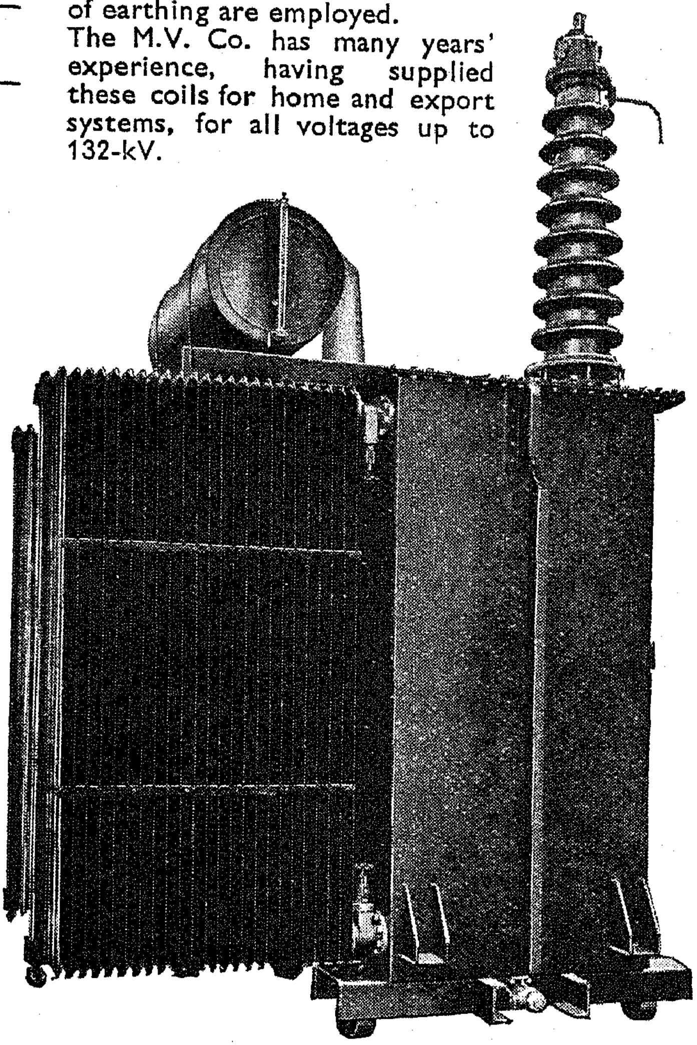
by installing
M. V. ARC
SUPPRESSION
COILS

The Arc Suppression Coil (connected between the neutral point and earth) prevents interruptions of supply due to line earth faults which are the principal cause of interruptions when other forms of earthing are employed.
The M.V. Co. has many years' experience, having supplied these coils for home and export systems, for all voltages up to 132-kV.





11-kV Arc Suppression Coil.



132-kV Arc Suppression Coil for 90 miles of Overhead transmission line.

METROPOLITAN
Vickers
ELECTRICAL CO., LTD.
TRAFFORD PARK ··· MANCHESTER 17.

E/A801

A manufacturer had his factory in a district where the Power Company offer a 10% rebate if the power factor is corrected to over 0·95. The cost of a Dubilier condenser to make this correction—or his "Capital Expenditure"—was £32 . 10 . 0. He had an annual consumption of 71,360 units and was paying 1½d. per unit, making his account £446 . 0 . 0. At the new rate, however, which came into force when the condenser was installed, he is saving £44 . 12 . 0 per annum—that is, obtaining a 137% dividend.

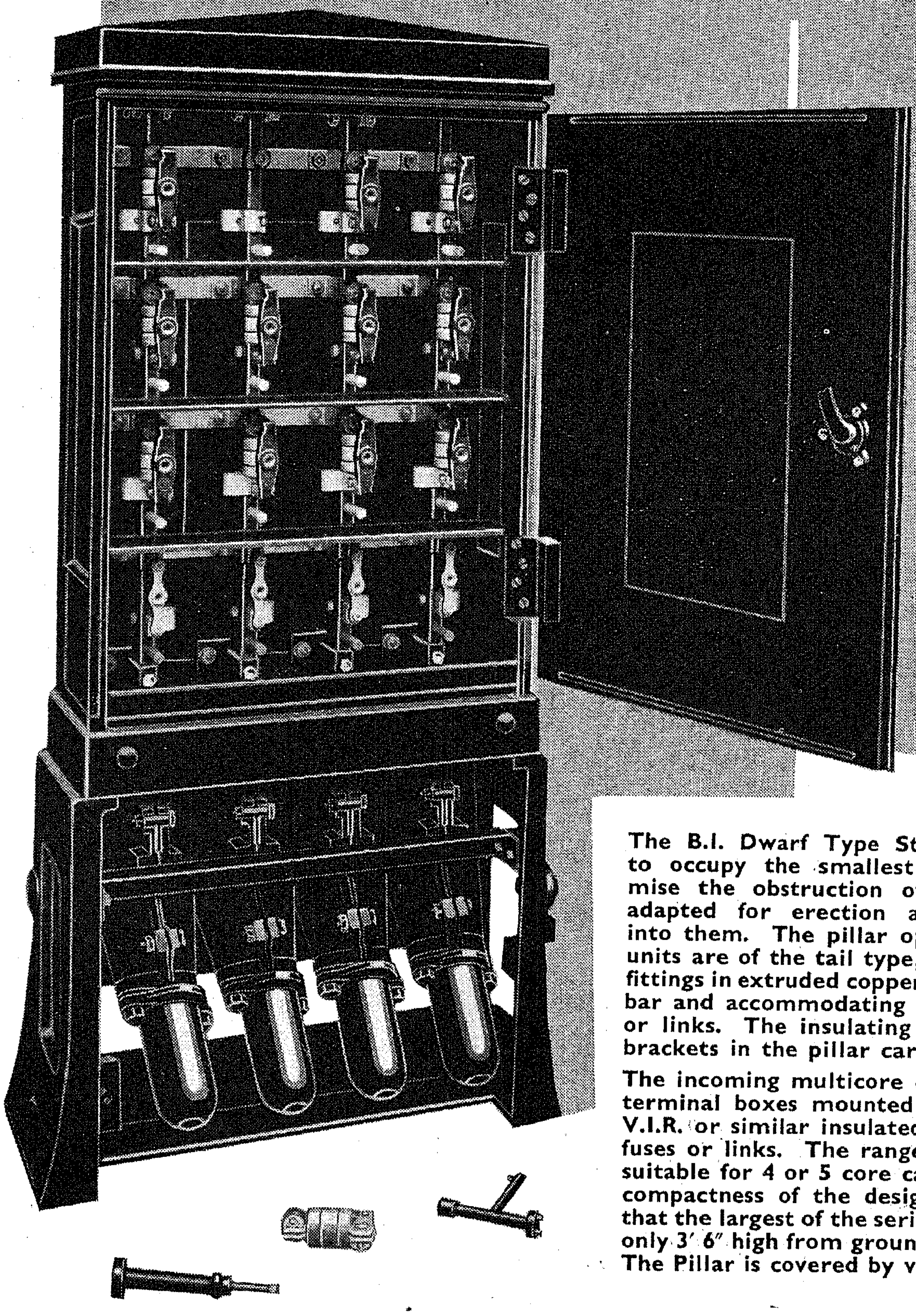
DUBILIER

POWER FACTOR CONDENSERS

DUBILIER CONDENSER CO. (1925) LTD., DUCON WORKS, VICTORIA ROAD, NORTH ACTON, W.3

C. R. Casson P.F.6

B.I. DWARF-TYPE STREET PILLARS



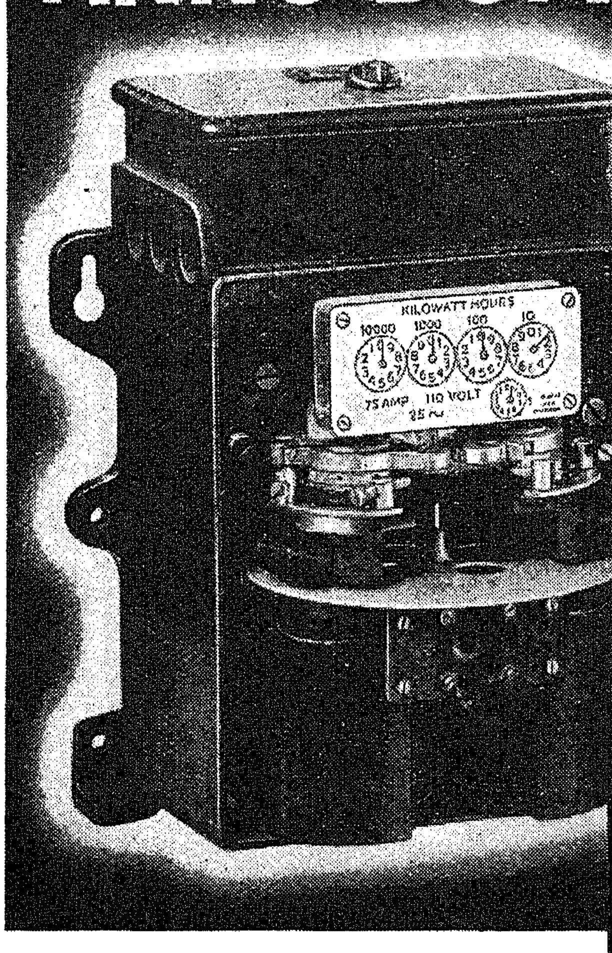
The B.I. Dwarf Type Street Pillar has been designed to occupy the smallest possible space and so minimise the obstruction of footways. These pillars are adapted for erection against walls or for building into them. The pillar opens only at the front and the units are of the tail type, consisting of cable and busbar fittings in extruded copper mounted on a robust insulating bar and accommodating High Rupturing Capacity fuses or links. The insulating bars are rigidly fixed to iron brackets in the pillar carcase.

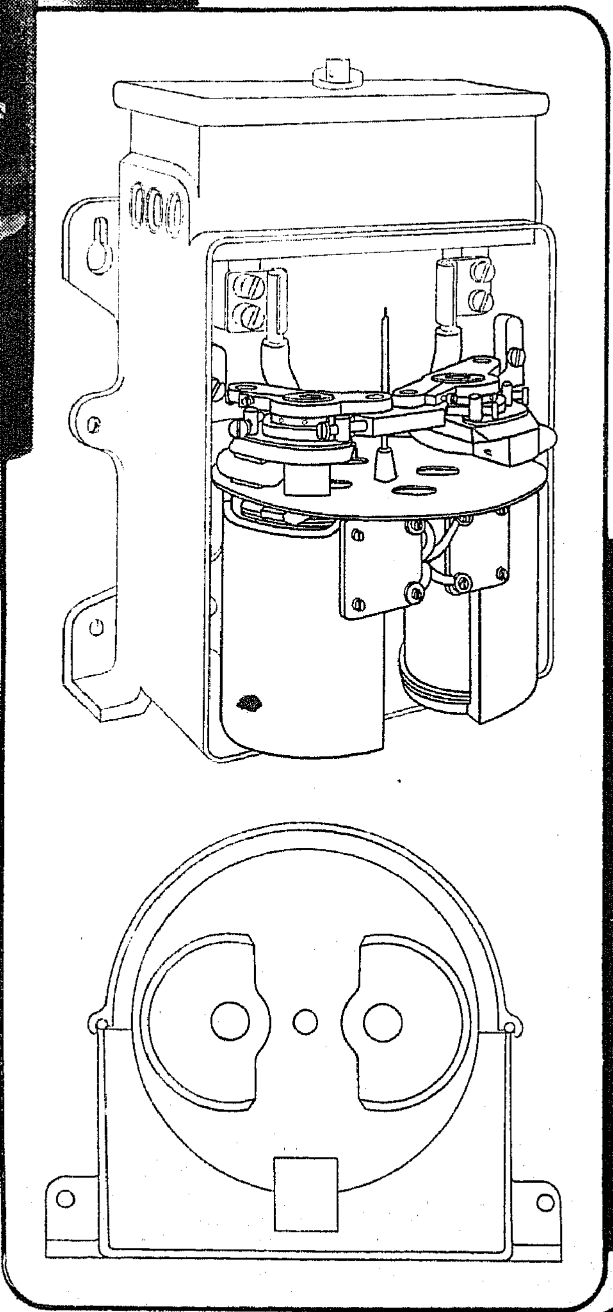
The incoming multicore cables are sealed in angle type terminal boxes mounted in the base of the pillar and V.I.R. or similar insulated tails taken therefrom to the fuses or links. The range consists of 4 or 6 way pillars suitable for 4 or 5 core cable, 150 or 300 amps., and the compactness of the design may be judged by the fact that the largest of the series, viz. the 6 way 5 core pillar is only 3′ 6″ high from ground level, 2′ 8″ wide and 9¼″ deep. The Pillar is covered by various British Patents.

BRITISH INSULATED CABLES LTD., PRESCOT, LANCS.

Tel. No. Prescot 6571. *London Office*, Surrey House, Embankment, W.C. 2. Tel. No. Temple Bar 7722

ANNO DOMINI 1906





...Pioneer work by Ferranti in Electric Metering

No.6

THE year 1906 saw the birth of a meter specially interesting as the prototype of the latest Ferranti Polyphase Meters, types FLy and FLx. It was, in fact, the first Ferranti Polyphase Meter, and it had two elements of the type B (described in advertisement No. 5 of the series) operating upon one disc.

F.M.65

FERRANTI Meters

No. 1 of the series

No. 2 of the series

No. 3 of the series

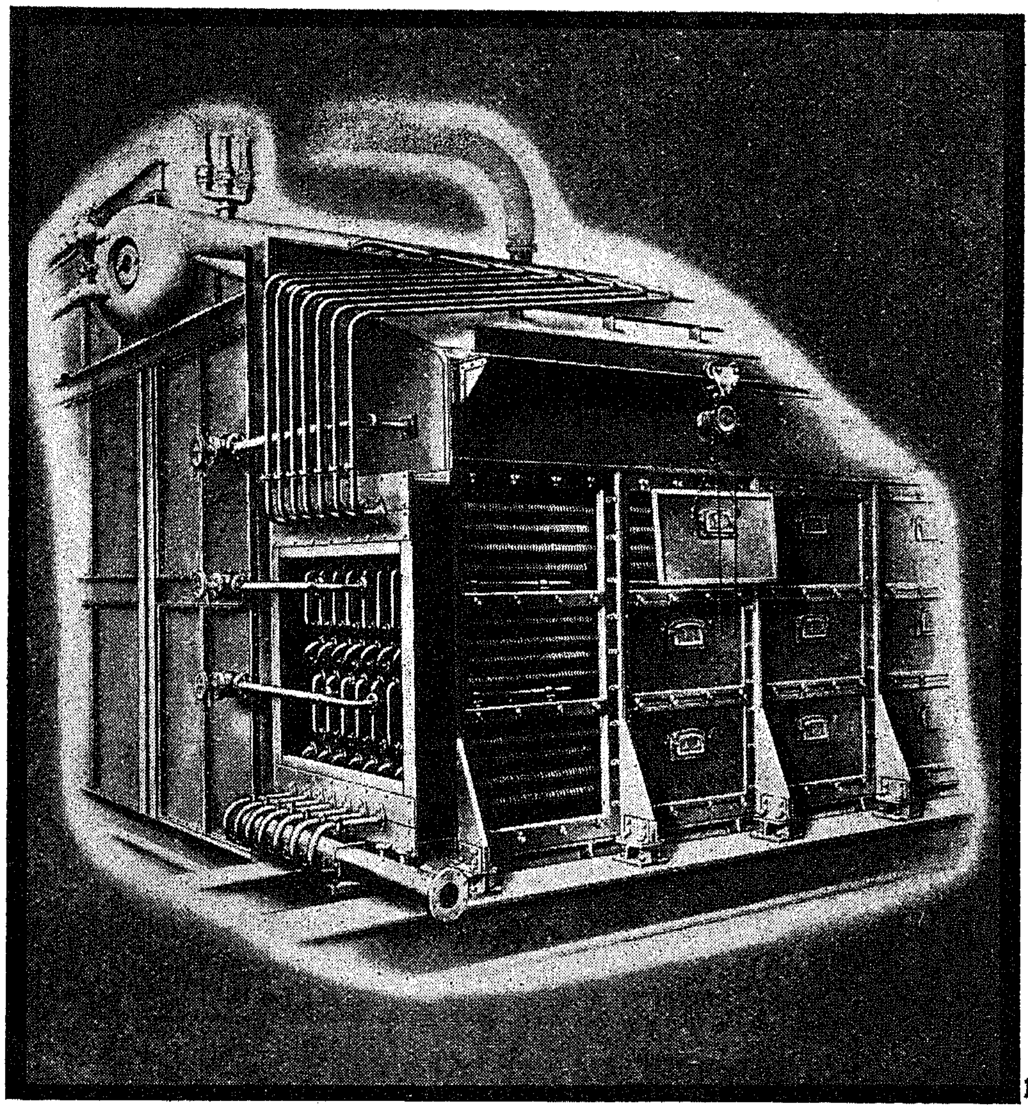
No. 4 of the series

No. 5 of the series

FERRANTI LTD., HOLLINWOOD, LANCS. *London Office:* BUSH HOUSE, ALDWYCH, W.C.2

Some important features of
THE FOSTER ECONOMISER

CONCENTRATED HEATING SURFACE—
JOINTS EXTERNAL TO GAS PATH—
CORROSION RESISTING CAST IRON
GILLED SLEEVES—EASY CLEANING—
DURABILITY AND DEPENDABILITY—



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E. GREEN & SON LTD.

WAKEFIELD

MAKERS OF ECONOMISERS SINCE 1854

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FANS
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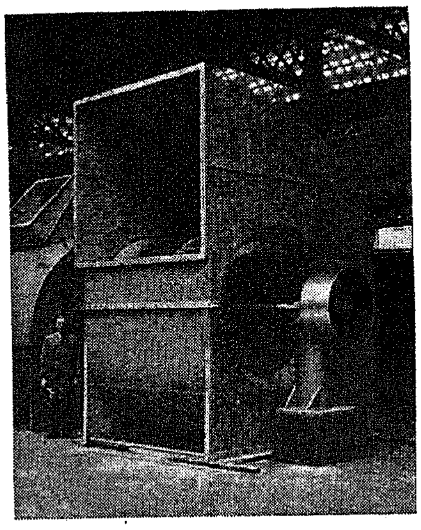
auxiliary equipment
for

Ventilating Buildings, Ships and Mines; providing Mechanical Draught on Boilers; blowing Forges, Furnaces and Cupolas; exhausting Metal Dust and Wood Refuse; removing Fumes, Smoke and Steam; Drying; Warming; Cooling; Refrigerating; Conveying; Cold Air Douche; Gas Boosting, etc.

Auxiliary Equipment: AIR HEATERS, FILTERS, WASHERS; DUCTWORK; HOODS; DUST SETTLERS; etc.



A large double-inlet Keith Centrifugal Fan photographed at our Works before despatch.

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Telephones: Central 7091 (9 lines)
Telegrams: "James Keith, Phone, London."

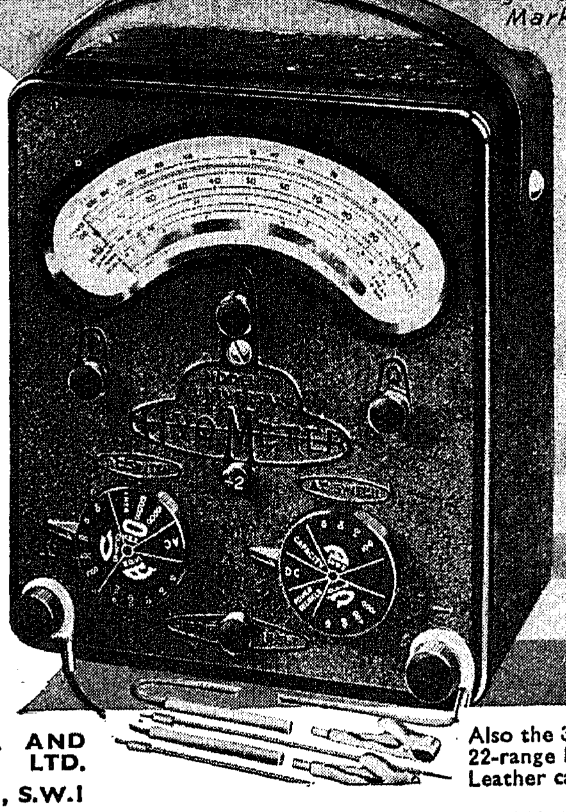
The 46-RANGE UNIVERSAL
AVOMETER
MODEL 7
Regd Trade Mark

This unique multi-range measuring instrument provides facilities for all electrical testing. It has 46 ranges, conforms with B.S. 1st Grade accuracy requirements, saves the cost of several separate instruments, and enables accurate measuring to be effected rapidly.

SPECIAL FEATURES: Ranges quickly selected by means of two rotary switches. Provides for measuring A.C. and D.C. amperes; A.C. and D.C. volts; resistance; audio-frequency power output; and decibels. No external shunts or series resistances. If an overload is applied, the instrument is automatically disconnected from the supply by a protective cut-out. Automatic temperature compensation.

16 Gns. *Resistance range extension unit (for measurements down to 1/100th ohm) 10/-*

- Write for fully descriptive pamphlet.



EVERY Electrical Measurement
A.C. and D.C. Amperes and Volts
RESISTANCE measurements
CAPACITY, POWER, DECIBELS
BRITISH MADE

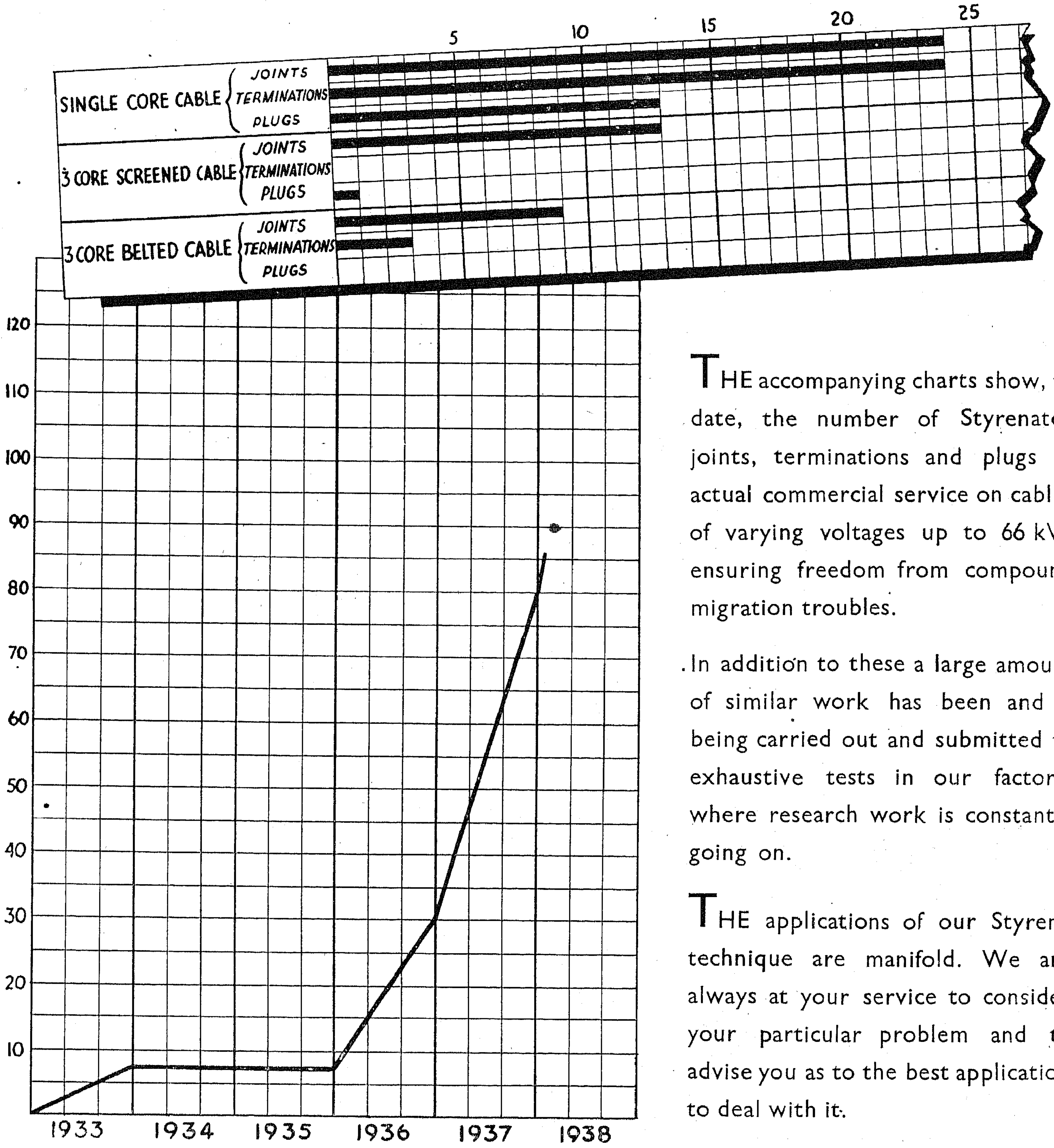
Also the 36-range Universal AvoMeter, 13 Gns.
22-range D.C. AvoMeter, 9 Gns.
Leather carrying case, 25/-.

Deferred terms if desired.

THE AUTOMATIC COIL WINDER AND ELECTRICAL EQUIPMENT CO., LTD.
Winder House, Douglas Street, London, S.W.1
'Phone: Victoria 3404-7.

STYRENATION

No. 7. PROGRESS.



THE accompanying charts show, to date, the number of Styrenated joints, terminations and plugs in actual commercial service on cables of varying voltages up to 66 kV., ensuring freedom from compound migration troubles.

In addition to these a large amount of similar work has been and is being carried out and submitted to exhaustive tests in our factory, where research work is constantly going on.

THE applications of our Styrene technique are manifold. We are always at your service to consider your particular problem and to advise you as to the best application to deal with it.

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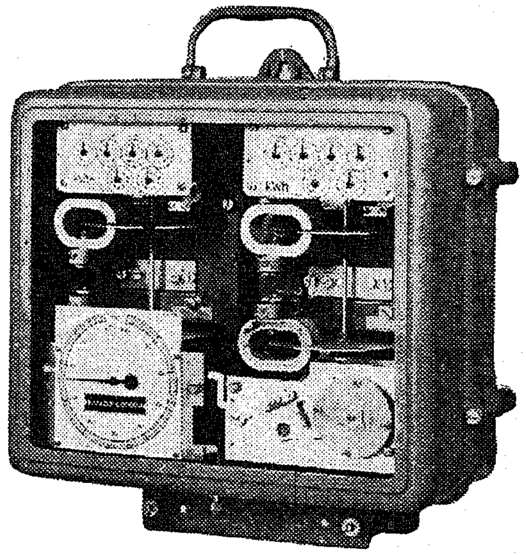
FREDERICK SMITH & COMPANY
(INCORPORATED IN THE LONDON ELECTRIC WIRE COMPANY AND SMITHS, LIMITED)
ANACONDA WORKS, SALFORD, 3, LANCS.

TELEGRAMS
"ANACONDA
MANCHESTER"



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WITH
K.V.A. DEMAND INDICATOR

SIMPLICITY—always a feature of C. & H. design—is strongly evident in this combination Meter. One set of terminals and connections ensures correct installation. The testing and adjustment of the meter is simplicity itself.

Manufacturers:
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INDUCTANCES & CHOKE COILS
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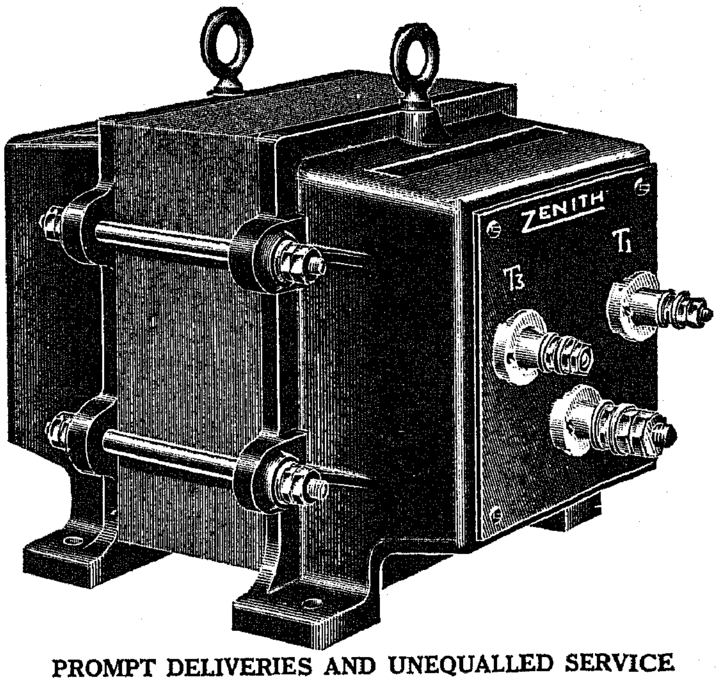

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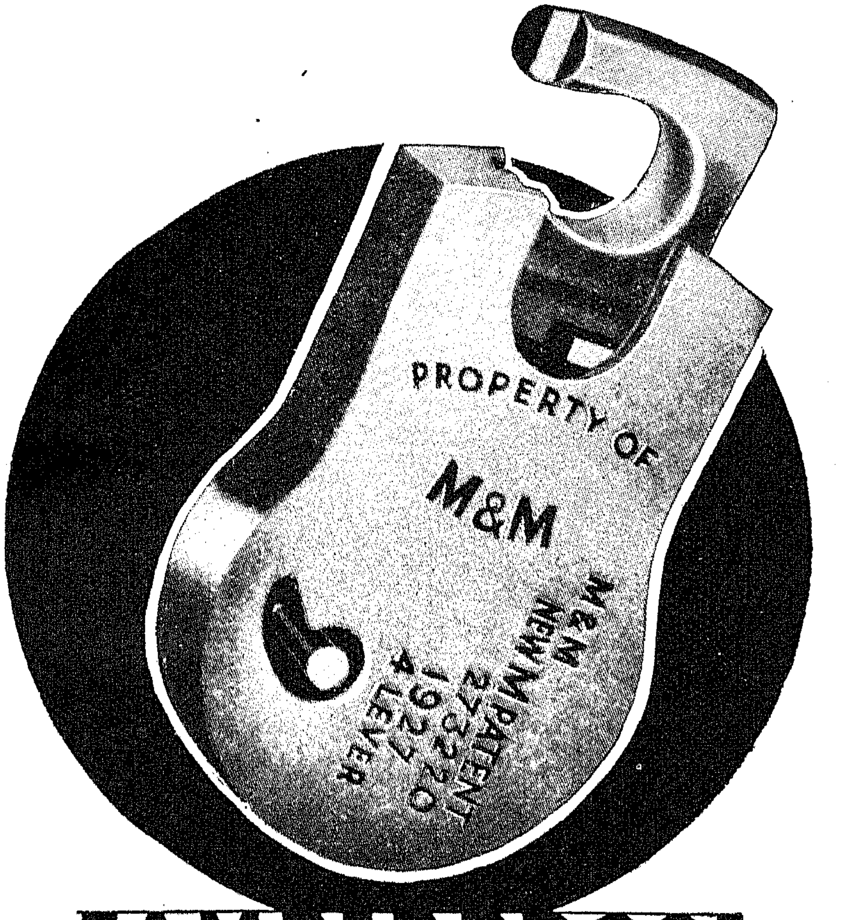

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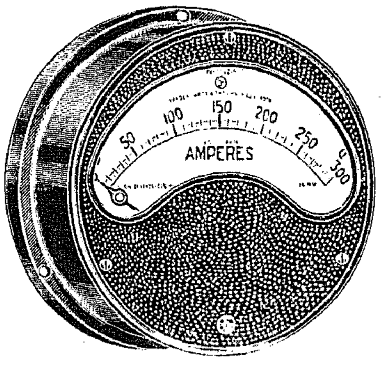

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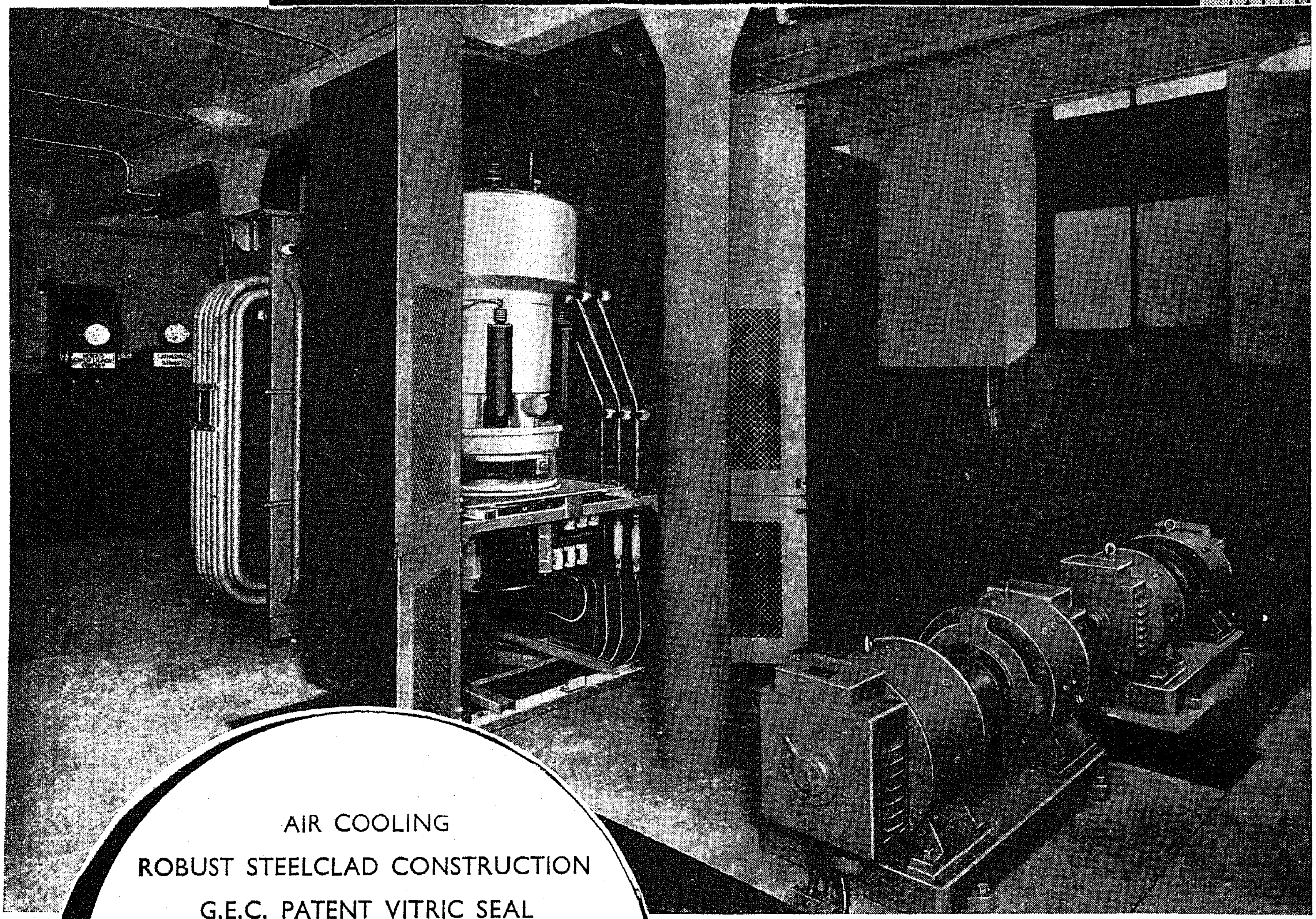

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